Date: 6/18/18

EIC Detector R&D Progress Report

Project ID: eRD1
Project Name: EIC Calorimeter Development
Period Reported: from 1/1/18 to 6/30/18
Project Leaders: H.Z. Huang and C. Woody
Contact Person: T. Horn, H.Z. Huang, E. Kistenev, S. Kuleshov, O. Tasi, C. Woody

Collaborators

S.Boose, J.Haggerty, J.Huang, E.Kistenev, E.Mannel, C.Pinkenberg, T. Shimek, S. Stoll and C. Woody
(PHENIX Group, BNL Physics Department)

E. Aschenauer, S. Fazio, A. Kiselev
(Spin and EIC Group, BNL Physics Department)

Y. Fisyak and W. Schmidke
(STAR Group, Physics Department)
Brookhaven National Laboratory

F. Yang, L. Zhang and R-Y. Zhu
California Institute of Technology

S. Ali, D. Damenova, J. Paez Chavez, R. Trotta, V. Berdnikov, T. Horn and I. Pegg
The Catholic University of America and
Thomas Jefferson National Accelerator Facility

W. Jacobs, G. Visser and S. Wissink
Indiana University

A. Denisov and A. Durum
Institute for High Energy Physics, Protvino, Russia

M. Battaglieri, A. Celentano, R. De Vita, L. Marsicano, P. Musico, M. Osipenko, M. Ripani and M. Taiuti
Istituto Nazionale di Fisica Nucleare, Sezione de Genova e
Dipartmento di Fisica dell'Universit`a, 16146 Genova, Italy

A. Sickles
University of Illinois at Urbana Champaign

C. Aidala, J. Osborn, M. Skoby
University of Michigan

Z.Shi
Massachusetts Institute of Technology

A. Brandin
B. MEPHI, Moscow, Russia

M. Josselin, Ho San, R. Wang, G. Hull and C. Munoz-Camacho
IPN Orsay, France

S. Heppelmann
Pennsylvania State University

C. Gagliardi
Texas A&M University

A. Somov
Thomas Jefferson National Accelerator Facility

B. Chen, R. Esha, H.Z. Huang, M. Sergeeva, S. Trentalange,
O. Tsai, and L. Wen
University of California at Los Angeles

Y. Zhang, C. Li and Z. Tang
University of Science and Technology of China

S.Kuleshov
Detector Laboratory of UTFSM, Valparaiso, Chile

H. Mkrtychyan, V. Tadevosyan and A. Asaturyan
Yerevan Physics Institute

Abstract

The eRD1 Collaboration – EIC Calorimeter Consortium has been working on various calorimeter R&D projects towards suitable detector technologies for a full azimuthal and pseudo-rapidity coverage in an EIC experiment. The UCLA team and the BNL team have been working on W-Powder/Scintilatting Fiber EMCal with SiPM readout for a compact detector of good energy/timing resolutions at mid-rapidity. The CUA team has been working on the $PbWO_4$ crystal detector technology for the very forward electron scattering direction with superior energy resolution. We report progresses from these ongoing R&D projects and plan for FY2019. In addition, the CUA team proposes to develop a ceramic glass detector technology for the intermediate pseudo-rapidity region where a detector with an excellent energy resolution detector and cost-effective technology will be needed; the UTFSM team proposes to develop the Shashlik detector technology for possible EIC application, which may provide a technology to accommodate easily projective detector geometry if needed.

For FY2019, the requested budget numbers are \$66.18k for the UCLA team, \$30k for the CUA team on the PWO crystal project. In addition, the CUA team requested \$30k for the glass detector project and the UTFSM tem requested \$75k for the Shashlik project. The overall budget request from the eRD1 collaboration – EIC Calorimeter Consortium is modest given the proposed R&D scopes involved. The proposed R&D activities cover the full spectrum of calorimeter technologies necessary for a full kinematic coverage of an EIC detector.

Sub Project: Progress on Tungsten Powder Calorimeter R&D by the UCLA/BNL/IU/PSU/TAMU team

Project Leader: H.Z. Huang and O. Tsai

What was planned for this period?

We planned to focus on studies of radiation damages of SiPMs, effects of annealing and investigate a scheme to use space–time evolution of hadron showers for significantly improving energy resolution of the outgoing hadron endcap calorimeter. In addition to these studies for the W/ScFi technology, we developed another idea of readout scheme for barrel EM calorimeter, which may be very cost-effective and more suitable for the EIC detector where event multiplicity is very low.

What was achieved?

A large sample of fully characterised SiPMs were placed at STAR IP for exposure during Run18, as of June 15 Run18 is still on-going and all these sensors are still being irradiated. The main goal of this radiation study is to verify our previous findings (reported six months ago) of a differential changing of breakdown voltage of SiPMs under irradiation. We may have new results by the time of the July R&D review meeting. Two undergraduate students are working with us for the measurements during summer.

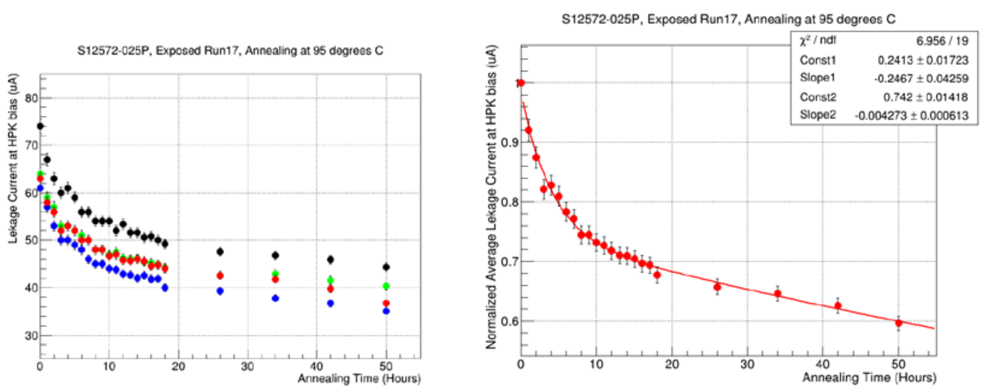


Figure 1. Annealing of exposed SiPMs and averaged over four sensors annealing curve (right).

With sensors exposed during Run 17 we performed passive annealing tests. We chose relatively safe temperature of 95 degrees C to avoid damages on other calorimeter components in case in situ annealing scheme will be needed in practice. A common approach is to fit annealing curve with a sum of exponentials (interpreted as due to different defects contributing to leakage current and they anneal with their different time constants). In our case a fit with two exponentials described data sufficiently well as shown in Fig 1. In about two days of annealing one can reduce damages accumulated in one year of running at the EIC in the forward HCal region to about 50% level. Practical realization of annealing scheme is still under investigation. One possible approach is to use direct bias (current) to heat the junction. This may be an efficient way to do annealing in situ and we want to investigate this option in future. Obviously, any annealing scheme will strongly depend on readout scheme, mechanical integration etc.

Future Plan:
We propose to continue our studies in the last two years. The main goal is to work towards a reliable, cost-effective calorimeter system with excellent performance that meet our physics requirements. Specifically, we plan to carry out two tasks for FY19.

Task 1.
Previously we reported of different methods of dealing with non-uniformities in light collection for highly granular, extremely compact electromagnetic calorimeters based on W/ScFi technology with SiPMs readout. Various techniques including filtering between fibers and light guide, usage of graduate reflectors at the back of the module and geometrical arrangement of the fibers (bending inward on sides and at the centre of the tower) were tested. Our latest design achieved quite satisfactory results for the forward EMcal. Here we propose to investigate very simple and very cost effective scheme for barrel EMcal, which could be a major advantage for the construction.
The occupancy and rates in the barrel region of the EIC detector are very low as shown in Figure 2 for top EIC energy configuration, taken from detector design studies at https://wiki.bnl.gov/eic/index.php/Detector_Design_Requirements.

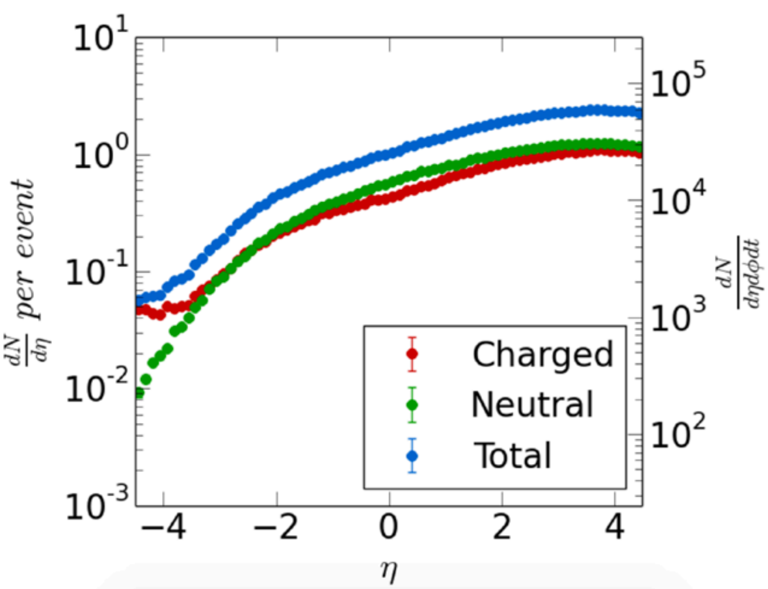


Figure 2. Occupancy and Rates for 20 x 250 GeV, instantaneous luminosity 10^{33} cm^{-2} s^{-1}

Previously proposed readout scheme for forward EMcal will lead to approximately 100k of readout channels in the barrel. We discussed about using multiplexing to reduce the cost of readout electronics. Another solution would be to use readout scheme conceptually similar to one used for KLOE and for GLUEX barrel calorimeters shown in Fig.3.

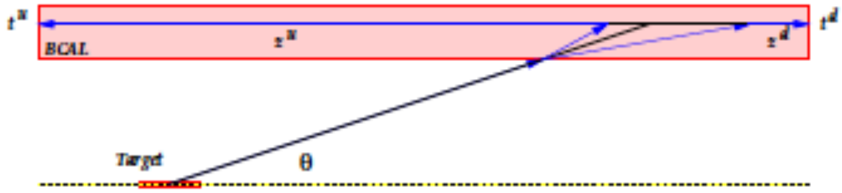


Figure 3. GLUEX Barrel Calorimeter Readout Scheme.

In both cases scintillation fibers run along the module and readout is located at the ends of the calorimeter. The calorimeter itself is finely segmented in phi and timing information is used to reconstruct z. In case of our design of W/ScFi barrel calorimeter a single WLS bar can be used to read entire raw of the towers as shown in Figure 4. Our estimate indicates that light collection efficiency for such scheme will be close to the one using short light guides.

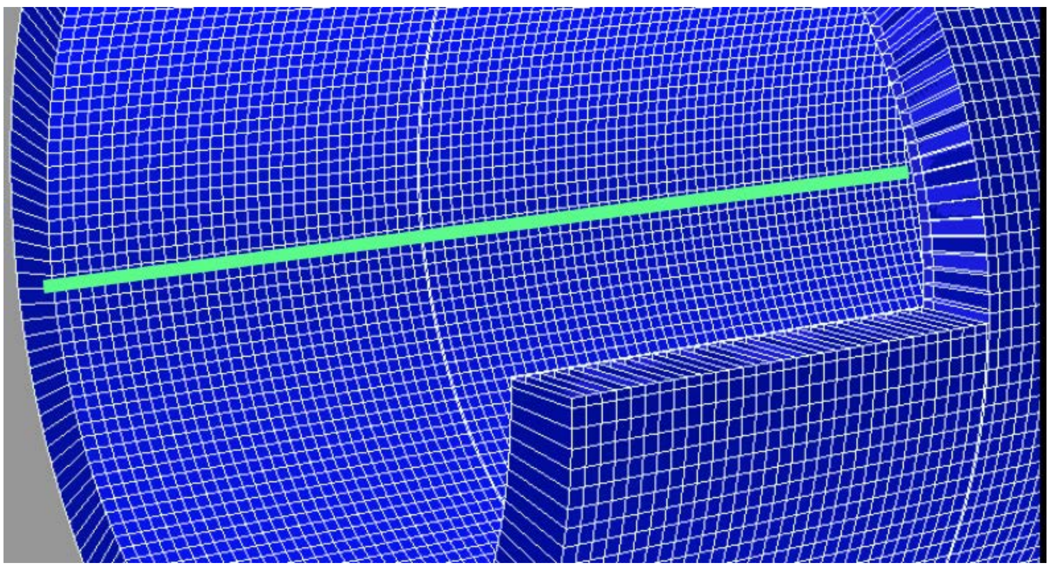


Figure 4. Readout W/ScFi barrel calorimeter with WLS bar.

There are numerous benefits of using such scheme:

- Reduction of readout channels by factor 150-200.
- Reduction of photo detectors by factor of 80 (reduction of cost and a noise in the detector due to degradation of SiPMs with exposure (for example, for jet patches when signal from ~30k SiPMs will be summed (4 SiPM/per tower)).
- Good uniformity of light collection.
- ‘Mixed light’ collection scheme, which is not sensitive to differential degradation of SiPMs under irradiation (constant term in energy resolution).
- Simple, mechanically independent readout and W/ScFi structure itself.
- Absence of active components inside the magnet, which require cooling/repairs etc.
- Ease of maintenance during long-term operation.
- Barrel calorimeter can be made completely gapless (as shown) and its readout components can be very thin saving precious space in a superconducting magnet.

We are proposing to test such scheme using our existing prototypes during test run at FNAL in April 2019 (test run already requested to calibrate STAR Forward Calorimeter system). Existing W/ScFi prototypes will require some modification. Test run needed to measure light yield, uniformity of response and energy resolution achievable with such scheme of readout for the same W/ScFi prototype we used in the past with the short light guides. We estimated that to carry out this test will require only about $10k needed to buy long WLS bars, adequate number of SiPMs, and to modify existing prototype mechanically (again, assuming we'll piggyback on the STAR test run).

Task 2.

During the last two R&D meetings, we mentioned about a new idea of using space-time evolution of hadronic showers to possibly dramatically (almost factor of two!) improve energy resolution of sampling hadronic calorimeters with a simple cost effective sandwich type technology. The idea was developed by E. Auffrey, A.Benaglia, P. Lecoq, M. Lucchini, A.Para, H. Wenzel and by P. Lecoq et al also through a TICAL ERC grant. Conceptually one can call it 'dual readout' technique, i.e. utilization of observable(s) which is correlated with the total number of neutrons released in the shower to make correction to the observed total energy on the event-by-event basis. Example of such observable is ratio of Cherenkov to Scintillation light in DREAM calorimeter, a technique developed in the past ten years by R. Wigmans et al. Timing information of shower development may be used in a similar fashion. In this case one uses scintillation signal only and the method should work for fiber and tile calorimeters. Figure 5 shows scatter plot showing ratios of Cherenkov-to-Scintillation for 50 GeV pions, and ratio of energy deposited in the first 1.25 ns to the total energy deposited in the calorimeter, as predicted by MC (IEEE Transaction on Nuclear Science, Vol.63,, No2, April 2016, A. Benaglia et al.). In both cases, a reliable correction to the total energy is possible on event-by-event basis.

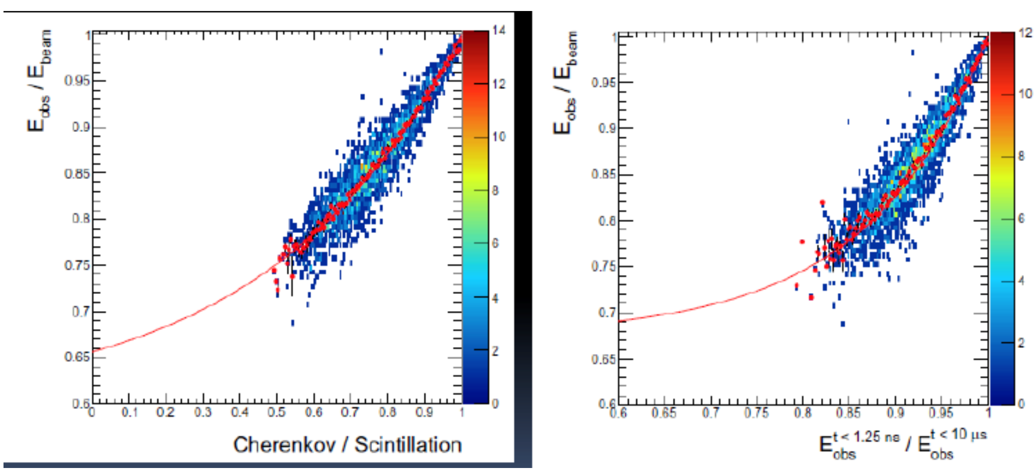


Figure 5. Dual readout technique using Cherenkov-to-Scintillation and Timing.

Authors of these cited papers investigated some instrumental effects (realistic light collection scheme, duration of the 'fast gate', shaped or raw signal from the photodetector) and concluded that the method is robust, i.e. one can extend 'fast gate' to 5 ns and use relatively slow LuAG scintillator without major impact on final result.

Energy resolution of hadron calorimeters can be dramatically improved using such technique as illustrated in Figure 6 (taken from above cited paper).

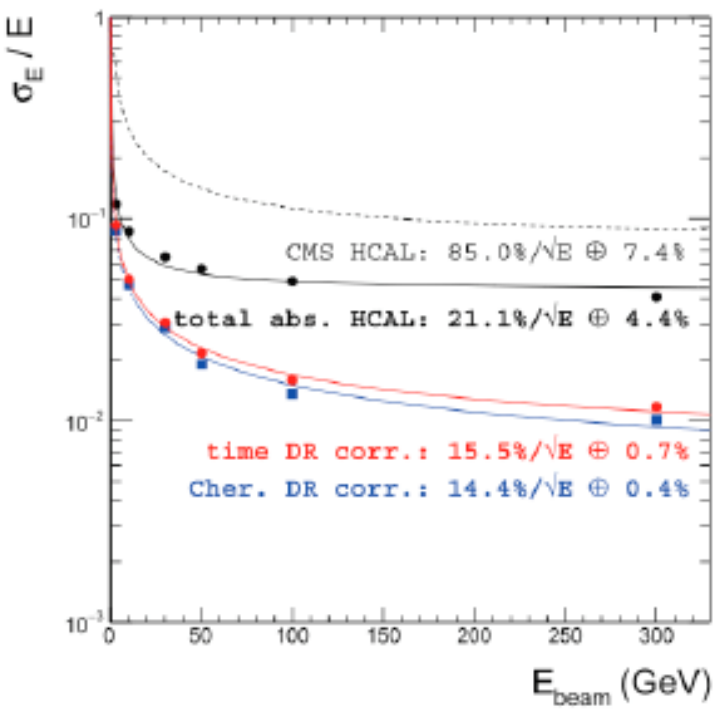


Figure 6. Black solid dots represent a fully sensitive 1 m x 1m x 3m iron block, red solid dots represent time based correction, blue Cherenkov-to-Scintillation DR correction. CMS beam test shown by the dashed line.

Note that dramatic improvement is for both stochastic and constant terms, which is in particular important for forward hadronic calorimeters at EIC.

Timing information was used in the past for e/h discrimination (in original SPACAL detector), and it was also used very effectively in ZEUS ZDC calorimeter (sandwich with WLS bar readout) to distinguish electromagnetic from hadronic showers.

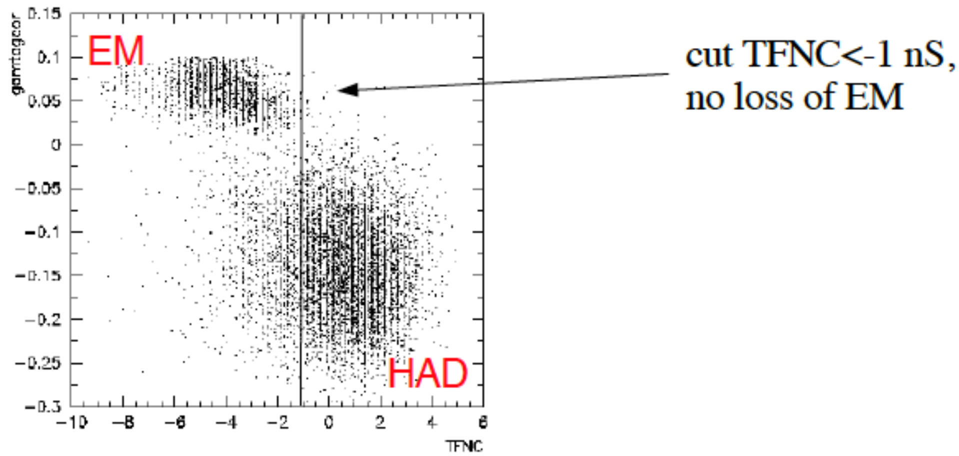


Figure 7. ZEUS FNC, Timing information to distinguish e/h showers. (Nucl. Instrum. Meth. A 565, 572 (2006) and Private communication B. Schmidke)

To summarize, simulations show that timing information of hadronic shower development can dramatically improve energy resolution of forward hadronic calorimeters for the EIC. There are indications such technique will work for simple tile/WLS bar structures as well (as was exploited in ZEUS FNC in Figure 7). However, there is no direct experimental confirmation yet and final proof will require a large (expensive) detector prototype at least 0.6 m x 0.6 m x 2m, i.e. detector similar to ZDC. It is also important to note that detector chemical composition may need to be optimized, because the number of neutrons produced and captured depends strongly on type of absorber, for example, thermalization time and capture time (as well as spatial extend) varies by order of magnitude for absorbers made of lead, iron and tungsten.

STAR Forward calorimeter test run at FNAL in April 2019 gives us opportunity to test this idea.

The plan we proposing is as follows. If we obtain proof-of-principle (stage 1), i.e. reproduce Fig. 5 results with small prototype, then we will carry out a full round of optimization with MC, followed by the construction of a larger version of the detector (stage 2). The full prototype at the end may be used as the ZDC for one of the EIC IP. We hope that the stage 2 may be funded through BNL LDRD or some other funding agencies because the cost of the proposed large-scale detector is expected to not fit in the current EIC detector generic R&D budget.

For stage 1 we propose to borrow some calorimeter parts from STAR Forward HCal, i.e. iron and lead absorber and scintillation tiles. Once STAR finishes test run program, we then will build with these parts two configurations we want to use for ‘timing’ measurements. Our estimation is that with two 8 hours shifts we may build 3 x 3 matrix about 8-interaction length long right at the test run site. We will need fast long WLS bars, which had to be purchased, fast PMTs, modification in mechanical structure and different DAQ with fast digitizers. We already arranged to borrow needed DAQ and digitizers (5GS/sec) form BNL. Optimization of possible configurations through MC will be performed prior to the test run.

Our proposed plan is a cost effective way to test this new interesting idea, which could greatly benefit the physics reach for hadronic calorimeter in general.

Budget Scenario	100%	20% cut	40% cut
UCLA support for students (26% overhead included)	$10.08k	$10.08k	$10.08k
Travel (26 % overhead included)	$12.6k	$12.6k	$12.6k
W/ScFi with WLS readout	$10k	0	0
HCAL WLS	$6k	$6k	$6k
HCAL Mechanical Components	$3k	$3k	$3k
HCAL Machine Shop (26% overhed included)	$9.5 k	$9.5k	$9.5k
HCAL PMTs	$15k	$15k	0
Total	**$66.18k**	**$56.18k**	**$41.18k**

With a 20% budget cut, we will drop Task 1 (it is nice to make such measurements with the beam during the planned STAR 2019 test run, but some of them can be made in the lab or later after the STAR test run).

With a 40% budget cut, we will have to delay the final testing if we cannot obtain suitable photo-detectors from somewhere else.

Sub Project: Progress on Tungsten Powder EMCal for sPHENIX
by BNL/UIUC/Michigan/MIT Team
Project Leader: C.Woody

Past

What was planned for this period?

Our main activity during the past 6 month period was to complete the construction of our V2.1 EMCAL prototype and test it at Fermilab. The V2.1 prototype consisted of sixteen 2D projective absorber blocks, each comprised of 2x2 towers forming an 8x8 array. Each tower was coupled to its own light guide that was read out with 4 SiPMs. The 2D projective absorber blocks were representative of the sPHENIX EMCAL at large rapidity ($\eta \sim 0.9$). The prototype incorporated virtually all aspects of the final calorimeter design, including the mechanical support of the blocks, electronics, cables, cooling and sector enclosure. Figure 1 shows the prototype after assembly and installation of all of its components. Additional information on the V2.1 is also given in our report from January 2018.

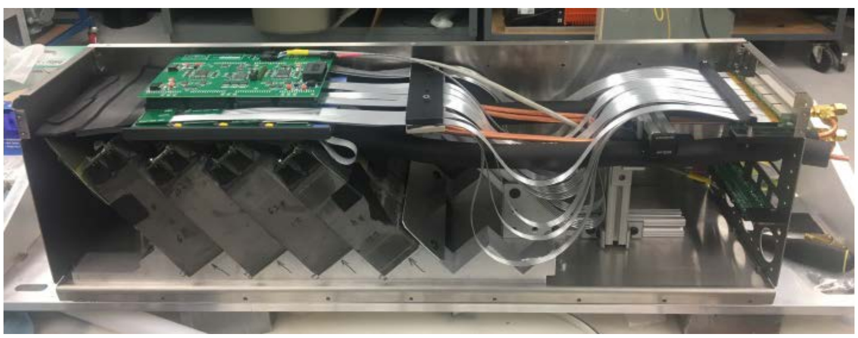


Fig. 1. sPHENIX EMCAL V2.1 prototype after assembly and installation of the readout electronics and cooling system.

The prototype was completed in early February 2018 and shipped to Fermilab for testing in the beam. Figure 2 shows the detector on the 2C motion table in the MT6.2 test beam area at Fermilab.

Fig. 2. V2.1 EMCAL prototype in the test beam at Fermilab.

The plan was to test the V2.1 prototype in a standalone mode in order to measure its energy resolution, linearity and uniformity of response. It was then going to be moved to the back of the test beam area where it would be mounted on the sPHENIX HCAL prototype where the two detectors would be tested together. However, after about a week of setup and running, we discovered a problem with the readout electronics which prevented us from taking all the data we wished to take. The detector was sent back to BNL in early April where the problem was diagnosed and fixed. It was then sent back to Fermilab in mid April and the rest of the stand alone data was taken. The final combined data with the HCAL was taken in mid May.

What was achieved?

Unfortunately, due to the delays in acquiring all of the data, and because of other meetings and priorities (in particular, an sPHENIX Workshop in China in mid April and the Quark Matter conference and sPHENIX CD-1 Review in mid May), the analysis of the test beam data has also been delayed and we do not yet have all of the results on the performance of the detector from the beam test. However, we do have some preliminary results from the uniformity study which we can compare to the uniformity of the V2 prototype that was tested last year. The V2 prototype was the first prototype built using 2D projective blocks and contained some of the first 2D projective blocks ever made. It showed effects of non-uniformity in the energy response at the boundaries between the blocks as well as the boundaries between the light guides which contributed significantly to the constant term in the energy resolution. We believed that the effects at the block boundaries were due in part to the poor quality of the blocks, many of which had fibers that were covered with tungsten powder and epoxy near the boundaries (a result of the fact that these were the first 2D blocks ever made), and the fact light from the fibers near the edges of the blocks was not being captured by the light guides. The V2.1 prototype has much better quality blocks, and also incorporated a feature in the block design where the fibers near the edges of the blocks were tapered inward towards the center of the block (see our report from July 2017). We believed that this would significantly enhance the light collection near the boundaries of the blocks and thus improve its uniformity of response.

Our preliminary results indicate that the uniformity was slightly improved by the new features incorporated into the blocks used in the V2.1 prototype, but the improvement is not dramatic. With the nominal tilt angles for the sPHENIX design of 10° in η and 5° in ϕ, the uniformity in the η direction improved somewhat at the block boundaries, but there was still a significant non-uniformity at the block boundaries in the ϕ direction. We therefore did an additional test of tilting the detector by 10° in ϕ, but the uniformities still did not improve dramatically. We are still in the process of trying to understand this effect while we continue to analyze the data.

sPHENIX also underwent its CD-1/OPA Review on May 23rd - 25th and the outcome was very successful. Aside from some minor changes that needed to be implemented in the cost and schedule, risk registry and various other parts of our documentation, it was concluded that sPHENIX was ready to proceed ahead to CD-2. We are now in the process of implementing all of those changes and expect to have our CD-2 Review sometime next year.

What was not achieved, why not, and what will be done to correct?

We did not take all of the data we needed to study the V2.1 prototype detector during the original time period we planned on at Fermilab (Feb 21-Mar 28) due to a problem we found with the EMCAL readout electronics. However, the detector was sent back to BNL where the problem was fixed, and was then sent back to Fermilab where the remaining data was taken in April and May. Due to these delays, and because of other important meetings that were happening during the same time period, we have not yet completed the analysis of the test beam data. We expect that this analysis will be completed during the next 4-6 weeks.

We also did not finish writing up our results on radiation damage in SiPMs that will be submitted for publication. However, we now have a nearly final draft which we hope to submit to the IEEE Transactions on Nuclear Science within the next few weeks.

Future

What is planned for the next funding cycle and beyond? How, if at all, is this planning different from the original plan?

Our main activity during the next six months will be to construct a preproduction prototype of a sPHENIX EMCAL sector. This will be one complete sector (which we call Sector 0) covering 1/32 in azimuth and ½ in rapidity that will incorporate all the features of the final calorimeter design. This will include the full mechanical structure, all the blocks covering the full rapidity range from $\eta = 0$ to $\eta = 1.1$, along with the fully instrumented electronics, cables and cooling system. Production of the blocks for Sector 0 will begin at UIUC in mid July and the assembly of the sector will begin at BNL around the end of the summer. In addition, plans are being made to produce 12 additional sectors (Sectors 1-12) following the completion of Sector 0 that will also be considered pre-production prototypes, but they should be fully functional and are expected to be used in the final sPHENIX detector.

What are critical issues?

The critical issues are to finalize the design of Sector 0, which include finishing and approving the final drawings and ordering of all the parts. This is now somewhat behind schedule due to the delays mentioned above, but we believe all the major issues have now been resolved and the design can be completed and approved during the few weeks. The next critical issue will be to keep the production of Sector 0 on schedule, and after that, to keep the production of Sectors 1-12 on schedule

Manpower

Include a list of the existing manpower and what approximate fraction each has spent on the project. If students and/or postdocs were funded through the R&D, please state where they were located, what fraction of their time they spend on EIC R&D, and who *supervised their work.*

The effort on the sPHENIX EMCAL is being carried out mainly by the BNL sPHENIX Group and the group at UIUC, with additional input and support on the electronics from the groups at the University of Michigan and Debrecen University in Hungary.

External Funding

Describe what external funding was obtained, if any. The report must clarify what has been accomplished with the EIC R&D funds and what came as a contribution from potential collaborators.

The effort on the sPHENIX EMCAL is being supported entirely by external funds. There is no support for these activities from EIC R&D funds.

Publications

Please provide a list of publications coming out of the R&D effort.

Our paper on our test beam results from 2016, “Design and Beam Test Results for the sPHENIX Electromagnetic and Hadronic Calorimeter Prototypes”, has been revised a second time and was resubmitted to the IEEE Transactions on Nuclear Science in June of 2018. With these revisions we expect the paper to now be accepted for publication.

We expect that our paper on our studies of radiation damage in SiPMs, “Results of the Effects of Neutron and Gamma Ray Irradiation on Silicon Photomultipliers” will be submitted to the IEEE Transactions on Nuclear Science by the end of the summer of 2018.

SubProject: Crystal Calorimeter Development for EIC based on PbWO4
Project Leader: T. Horn

High resolution calorimetry is critical at the EIC in the two endcaps for particle identification and reconstruction. In the electron endcap, particle identification is important for discriminating single photons from, e.g., DVCS and two photons from π^0 decay , and e/p. Resolution is essential for particle reconstruction, which is driven by the need to accurately reconstruct the four-momentum of the scattered electrons at small angles. There, the angular information is provided by the tracker, but the momentum (or energy) can come from either the tracker or the electromagnetic calorimeter. At rapidity < -3 the energy measurement comes mainly from the calorimeter. As described in our January 2017 report, resolution helps to extend the useful y-range and "purity" in x/Q^2 bins. To make a clear positive impact on the scattered electron kinematics determination the requirements on the inner calorimeter are:

1. Good ***resolution in angle*** to at least 1 degree to distinguish between clusters,
2. ***Energy resolution*** $(1.0\% - 1.5\%)/\sqrt{E} + 0.5\%$ to measure cluster energy,
3. ***Time resolution*** to < 2ns
4. Ability to withstand radiation down to at least 1 degree with respect to the beam line.

A solution based on $PbWO_4$ is optimal due to its small Moliere radius (R_M=2.0 cm), high density (8.3 g/cm^3), fast response, and radiation resistance.

The critical aspect for ***crystal quality, and thus resolution performance*** of the EIC inner endcap calorimeter, is the combination of high and uniform light output and radiation hardness, which depend on the manufacturing process. Our previous studies have shown that there is significant crystal-to-crystal variation for crystals manufactured by SICCAS. ***Evaluation of the variation in chemical composition and optical properties from crystal to crystal and, together with vendors, possibly determining the origin of it is thus one of the main goals of this R&D project.*** This information will be important for what is acceptable for the EIC inner endcap calorimeter. Our previous studies showed that the constant term, which includes several systematic effects like nonlinearities in light collection, which are in part properties of the crystal itself, has a large impact on the response parametrization. ***Another main goal of this R&D project over the next year is thus to construct a prototype and to carry out a test beam program to establish limiting resolution and uniformity, as well as analysis of the constant term.*** The construction of a prototype and availability of a sufficient number of quality crystals is critical. The prototype will also allow for testing different readout systems.

Past

What was planned for this period?

- ***Crystal characterization for crystal specification and impact on EIC detector performance, e.g. reduction of non-uniformities***
    - Characterize, including chemical analysis, 460 SICCAS crystals produced in 2017 in collaboration with the NPS project
    - Evaluate crystal geometry and surface and provide feedback to vendors
    - Procure 450 crystals from CRYTUR in collaboration with the NPS project
- ***Analysis of constant term and establish limiting energy resolution and uniformity***
    - Model energy resolution, e.g. simulate the impact of miscalibrations and dead zones between crystals
- ***Design a test beam program to establish limiting energy resolution and uniformity***
    - Design prototype including readout system and temperature monitoring
    - Develop analysis/calibration software for prototype and test beam program
    - Investigate different readout options to be tested with a prototype

What was achieved?

With commitment of internal university and laboratory funds and through synergy with the NPS project at JLab we managed to partially carry out crystal characterization at CUA and IPN-Orsay for crystal specifications and impact on EIC detector performance. We also developed a simulation to model the impact of, e.g. miscalibrations on detector resolution, and in particular the constant term. Our activities are listed below. Please refer to the appendix for additional information.

- Performed simulations to analyze impact of reflector, miscalibrations, and material between crystals, etc. on calorimeter resolution, and in particular the constant term.
- Designed a test beam program for prototype tests in collaboration with the NPS project
- Tested the optical properties of a set of 460 crystals produced at SICCAS in 2017, procured through synergy with the VSL and the NPS project, including systematic uncertainty studies.
- Provided feedback to vendors and iterated on ways to reach required crystal quality, e.g. chemical composition, reducing bubbles/cracks inside the bulk, and crystal surface properties. Evaluated benefit of rectangular crystals for EIC calorimeters
- Submitted procurement for 400 SICCAS and 100 CRYTUR crystals through synergy with NPS project

What was not achieved, why not, and what will be done to correct?

No efforts on prototype construction were made as in the Committee's July 2017 report, it was explicitly stated that "*Prototype construction at this stage is not* *encouraged*". However, as noted in the Committee's January 2018 and 2017 reports it is "*of great interest to see the real limiting behavior [of $PbWO_4$ crystals], including uniformity of response, calibration precision, rear leakage of showers, dependence on angle of incidence, and amount of allowable dead zone between towers*". The only practical way to do this is to construct a prototype and measure these properties with beam. In anticipation of the Committee's approval to proceed with a prototype construction in FY19, we designed a test program and developed the initial components of it in collaboration with the NPS project.

Future

What is planned for the next funding cycle and beyond? How, if at all, is this planning different from the original plan?

We plan to construct a prototype and carry out a test program with beam to establish the limiting resolution, and uniformity. We also plan to continue crystal characterization including optical, chemical composition and surface studies for additional samples, and our communication with vendors. This is essential as over the last funding cycle it has become apparent that there is still significant manufacturing uncertainty for $PbWO_4$ crystals. Our planned activities for the crystal R&D project are in order of priority:

- Construct a prototype and carry out a test beam program to establish actual crystal performance, limiting resolution and uniformity with available SICCAS or CRYTUR crystals
- Iterate with vendors on crystal requirements and manufacturing process optimization
- Procure in collaboration with NPS project 450 crystals from SICCAS or CRYTUR

What are critical issues?

At this stage, the most critical issue is to construct a prototype, which is required to pursue a test beam program as already recommended by the Committee in the January 2018 report. At the same time, it is important to continue communication and iterations with the two vendors of $PbWO_4$ crystals to ensure that high quality crystals will be available for EIC.

Additional information:

There have been considerable delays in procuring a large quantity of rectangular crystals from CRYTUR. These are due to delays on the side of the company in obtaining parts and assembling the required crucibles and furnaces. The company estimates that the method for growing rectangular crystals with specifications for the NPS project will be ready towards the end of summer 2018. The company is also concerned about capacity. With obligations of a few hundred crystals made towards PANDA, only about 100 crystals can be made for NPS or other non-PANDA purchases in 2018.

Obtaining a large quantity of crystals from SICCAS appears possible even though quality control remains an issue. Over the last year, almost 50% of the set of 460 crystals from 2017 had to be rejected. However, the company is willing to discuss optimizations of their procedures and implementing stricter quality control measures. A meeting with representatives of is planned for summer 2018.

Funding Request and Budget

Table 3. Funding by task

Item	FY19 ($K)	FY20 ($)
Materials for glass production	5	5
Technical Support	15	20
Parts for prototype and construction		10
Travel	10	15
Total	**30**	**50**

Table 4. Funding by Institution

Institution	FY19 ($K)	F20 ($k)
CUA	15	20
IPN Orsay	10	15
Caltech	5	15
JLAB		
BNL		
Total	**30**	**50**

Budget scenarios and impact statement: Our main goal over the next year is to construct a prototype and to carry out a test beam program to establish limiting resolution and uniformity, as well as analysis of the constant term. We will also continue to evaluate crystals and remain in close communication with vendors to make sure that high quality crystal are available for EIC.

In the case of a 20% cut, we would be able to produce additional simulations of the impact of crystal properties on detector resolution, and in particular the constant term. However, we would have to delay the construction and test program with a prototype, which would impact our ability to determine the real limits of position and energy resolution of the material for application in EIC calorimeters.

In the case of a 40% cut, we would not be able to construct and test a prototype to determine the real limits of resolution of the material for EIC. Our focus would mainly shift towards the NPS project, which would be the funding source for our activities, and we may only provide information relevant specifically for EIC, as possible.

Manpower

Include a list of the existing manpower and what approximate fraction each has spent on the project. If students and/or postdocs were funded through the R&D, please state *where they were located, what fraction of their time they spend on EIC R&D, and who supervised their work.*

IPN-Orsay
M. Josselin
Ho San, graduate student
R. Wang, postdoc
G. Hull
C. Munoz-Camacho

CUA
S. Ali, graduate student
D. Damenova, high school
J. Paez Chavez, high school
R. Trotta, graduate student
V. Berdnikov, postdoc
T. Horn
I. Pegg
Vitreous State Laboratory

Yerevan
H. Mkrtchyan
V. Tadevosyan
A. Asaturyan

BNL
C. Woody
S. Stoll
M. Purschke

Caltech
R-Y Zhu

External Funding

Describe what external funding was obtained, if any. The report must clarify what has been accomplished with the EIC R&D funds and what came as a contribution from potential collaborators.

- All of the FTEs required for working towards finalizing the crystal test setup and crystal characterization are provided by CUA/VSL/IPN-Orsay or external grants. The absence of any labor costs makes this proposed R&D effort extremely cost effective.
- The 460 SIC crystals produced in 2017 are provided through synergistic activities with independent research for the JLab Neutral Particle Spectrometer (NPS) project.
- The expertise and use of specialized instruments required for crystal characterization and their chemical analysis, as well as additional crystals samples

are made possible through collaboration with the Vitreous State Laboratory (VSL) at CUA that is also collaborating on the NPS project.

Efforts related to crystal studies as described here were accomplished with external funds through synergistic activities with the NPS project at JLab. Additional funds and facilities for crystal characterization were provided by the Vitreous State Laboratory at CUA. Salaries and wages were provided by private external grants from the individual principal investigators, e.g., IPN-Orsay, Yerevan, and the National Science Foundation.

Publications

Please provide a list of publications coming out of the R&D effort.

C. Munoz-Camacho et al., "*R&D for high resolution calorimetry at the future Electron-Ion Collider*", Presentation at the XVIIth International Conference on Calorimetry in Particle Physics, 15-20 May, 2016, Daegu, South Korea

Through synergy with the NPS project at JLab:

R. Trotta et al. "*Exclusive reactions and the PbWO4-based Inner Calorimeter for the Electron-Ion Collider*" presentation at the APS April 2017 meeting, Washington, DC

T. Horn, C. Munoz-Camacho, C. Keppel, I. Strakovsky et al., arXiv:1704:00816 (2017) "*Workshop on High-Intensity Photon Sources (HIPS2017) Mini-Proceedings*"

T. Horn et al., J.Phys. Conf. Ser. **587** (2015) 1, 012048 "*A PbWO4-based Neutral Particle Spectrometer in Hall C at 12 GeV JLab*"

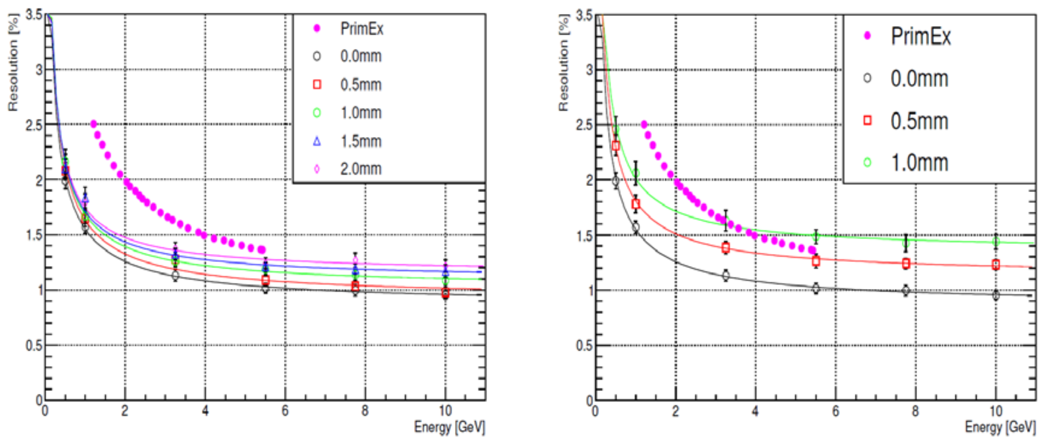
T. Horn et al. "*Physics Opportunities with the Neutral Particle Spectrometer in Hall C*", presentation at the APS DNP 2015 Fall meeting, Santa Fe, NM

Appendix

Projections of Resolution – Simulation Studies

We developed a GEANT4 simulation to study the impact of reflector material, dead zones between crystals, and miscalibrations on resolution. The simulation uses an array of 1116 $PbWO_4$ crystals stacked in the form of a 31x36 matrix. Each of the crystals is wrapped with VM2000 reflector. PMTs are coupled at the backside of each of the crystals with optical grease. Each of the crystals is supported by a carbon frame with density of 1.55g/cm^3. For reference, we also present results with a gap of air (instead of carbon) between the crystals. Crystals have dimensions of 20.5 x 20.5 x 200.5 mm^3 and the wrapping has a thickness of 65μm. Each of the crystals has optical properties of the $PbWO_4$ measured by R.Y. Zhu et al. (Zhu, 1996). PMTs dimensions are 20.5 x 20.5 x 20.5mm^3 in order to make no light leaks when photons travel from the crystal to the PMT.

Fig. 1 shows the effect on the energy resolution of the size of gaps between crystals as part of the mechanical design. The statistical term is roughly unaffected, but this impacts the constant term directly, as illustrated in Fig. 2.



(a) Air gap (b) Carbon gap

Fig 1: *Energy resolution as a function of the gap size between crystals.*

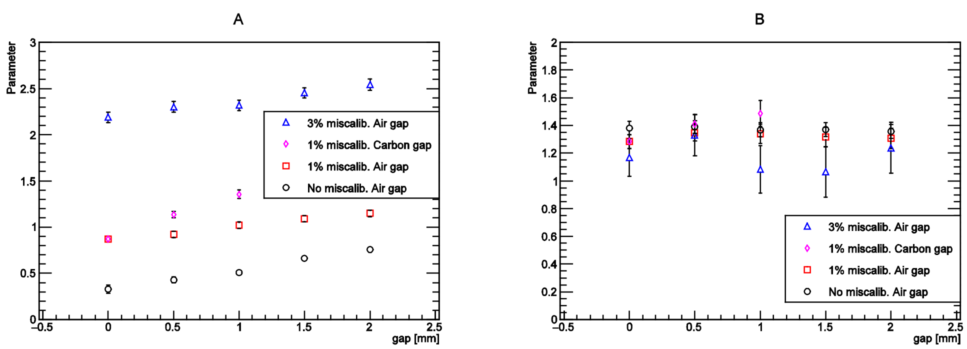


Fig 2: *Constant term (A) and statistical term (B) of the energy resolution for different simulated conditions ($\sigma(E)/E=A+B/\sqrt{E}+C/E$).*

Initial Design of a Test Beam Program

A measurement with a prototype will allow to establish the limiting energy and position resolution of the material – by comparing measured to expected light output. We plan to use the prototype together with simulations to evaluate contributions to the overall resolution including uniformity of crystal response and statistical fluctuations of containment losses. These studies will naturally include calibration of the precision among crystals, dependence on incidence angle and spacing between the crystals.

Energy and position resolution can be established in test beam. The prototype could be calibrated with the tagged photon beam at Jefferson Lab. The basic principle of this test program is as follows. One tags the bremsstrahlung produced by a monoenergetic electron beam up to 11 GeV. After bremsstrahlung emission, the electrons are analyzed by the magnetic spectrometer of the tagger requiring a coincidence of the bremsstrahlung photon with the corresponding electron in the focal plane.

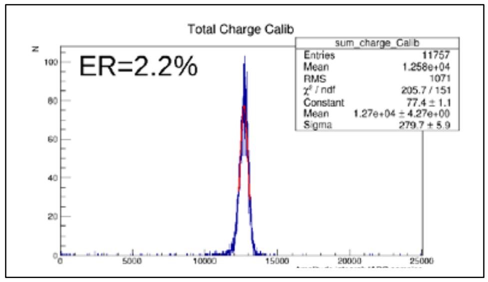


Fig 3: *(left) NPS 3x3 $PbWO_4$ prototype installed in Hall D at Jefferson Lab in 2018, (right) result for 4.69 GeV electrons from the initial energy calibration in April 2018 before optimization.*

The NPS 3x3 $PbWO_4$ shown in Fig. 3 (NPS 10x10 $PbWO_4$ or the envisioned EIC 5x5 prototype) array is composed of 9 rectangular blocks (100 or 25 blocks, respectively), 200mm long and of 20x20 mm^2 cross section. The 3x3 prototype could be easily adapted for EIC prototype studies. The prototype includes a temperature monitoring system. The prototype would be located at a position downstream of the radiator. A set of collimators can be used to control the beam spot on the front face of the crystals. The crystal matrix could be moved via remote control in two dimensions perpendicular to the axis of the collimated photon beam by stepping motors to perform a relative calibration of each detector element. This technique has been used successfully March-May 2018 for NPS $PbWO_4$ prototype tests[1].

Crystal Characterization and Systematic Uncertainty Results

Radiation hardness measurements were performed in Orsay using an intense ^{60}Co source and compared with those performed at Giessen on the same set of 9 SICCAS crystals. Very special care was take to reproduce the same experimental conditions between the setups concerning both radiation integral dose and dose rate. Fig. 4 shows the setup in Orsay where the dose rate can be changed by varying the distance of the 9 cells containing the PWO crystals from the 3000 Cu ^{60}Co source. The dose rate was accurately measured using Fricke dosimetry, which consists on measuring the absorption of light produced by the increased concentration of ferric ions by ionizing radiation in a solution containing a small concentration of ammonium iron sulfate. The linear absorption with time at a given position determines the exact radiation dose received by the crystal when placed at the same position as the solution.

[1] The authors from CUA, IPNO and Yerevan have carried out these prototype tests and are part of the NPS collaboration

Fig 4: *Irradiation setup in Orsay using a high activity ^{60}Co source. Crystals are placed in containers where the radiation dose was previously measured using a Fricke solution.*

The average dose to each crystal is within 15% to each other and at 60cm from the source within 10% of the dose rate used at Giessen. Fig. 5 shows the longitudinal transmittance measured before T_b and after T_a an average of 30 Gy integral dose to each crystal, compared to the measurements performed in Giessen in the same crystals, and displayed as $dk=ln(Tb/Ta)/d$, where $d=20$ cm is the longitudinal distance in Fig. 6. As the plots show, the radiation hardness varies significantly from one crystal to another, and these differences are even noticeable by visual inspection (Fig. 7 shows the crystals after 30 Gy of radiation). However, the agreement between the measurements performed in Orsay and Giessen is very good.

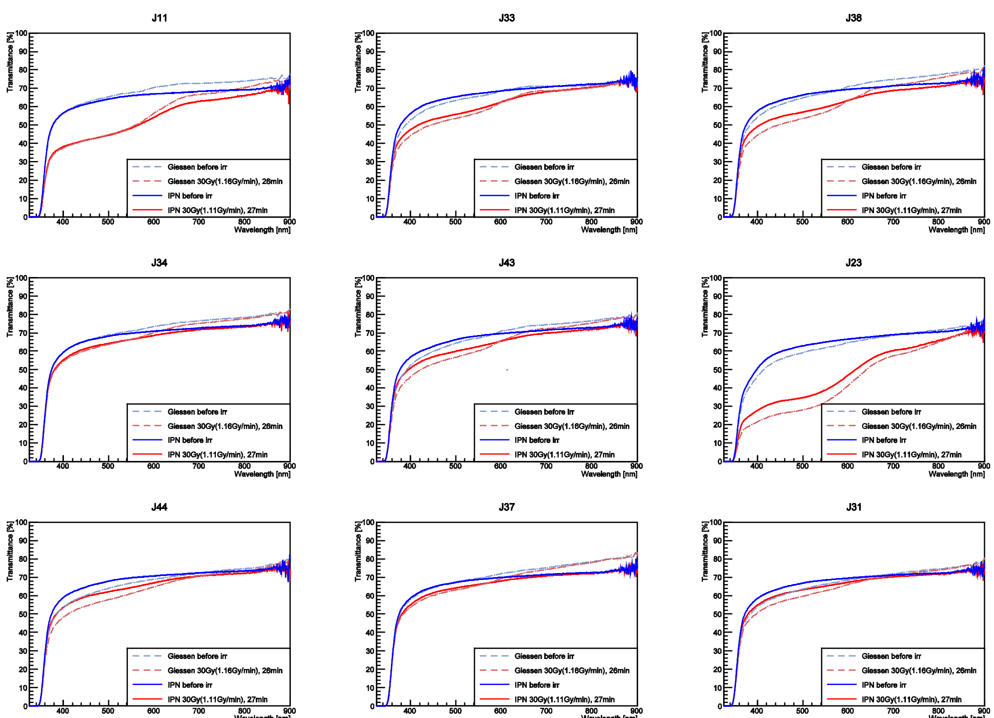


Fig. 5: *Transmittance before and after 30 Gy dose at ~1 Gy/min rate at Giessen and Orsay on the same set of 9 SICCAS crystals.*

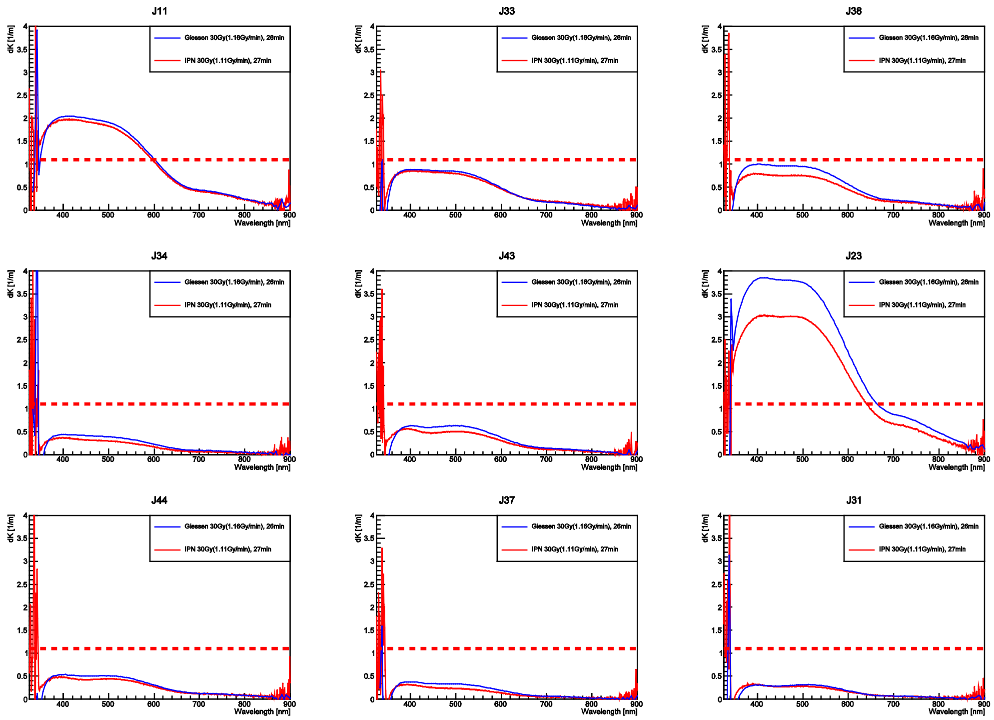


Fig. 6: *Comparison of dk for 30 Gy dose at ~1 Gy/min rate at Giessen and Orsay. The horizontal line at dk=1.1 m^{-1} is the acceptance limit of the PANDA experiment.*

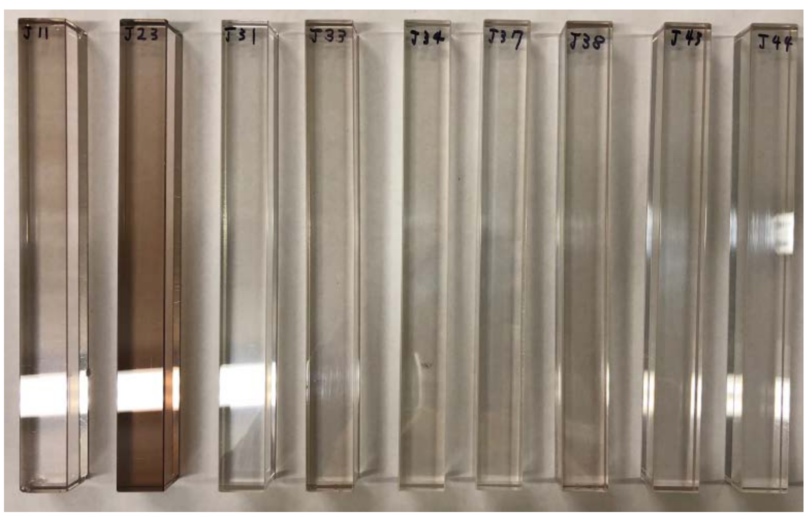


Fig. 7: *Visual inspection of crystals after 30 Gy of radiation at 1Gy/min..*

Iteration with vendors towards optimized crystal properties

Evaluation of the set of 460 SICCAS crystals produce in 2017 had nearly half fail the NPS requirements. The reasons for failure for 30% of these can be categorized in three categories: 1) Light Yield @420nm < 60%, 2) Chips, scratches, marks of old labels, 3) Bubbles and other internal defects. An excerpt of crystal performance characterization is illustrated in Fig. 8. Discussions with the company to address these, and in particular the internal defects, which directly affect uniformity and thus resolution, is ongoing.

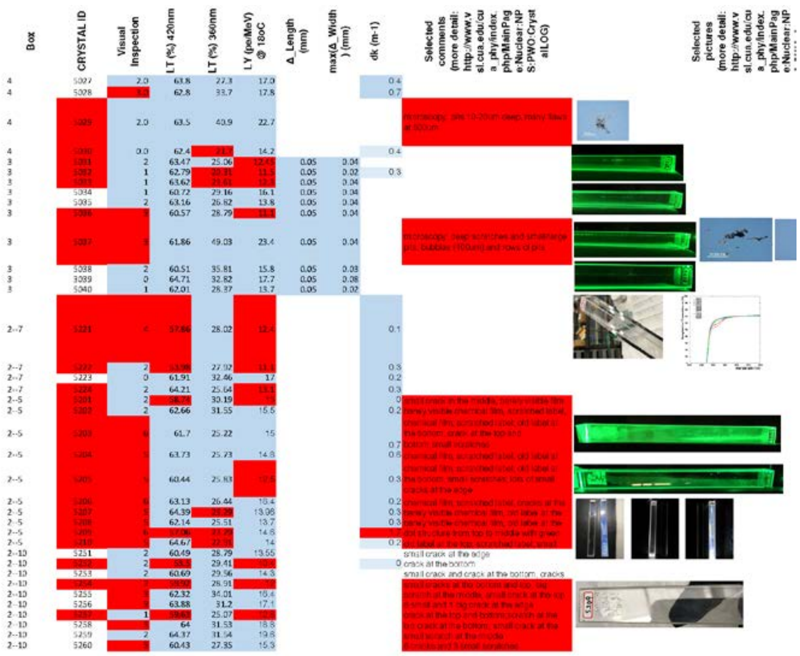


Fig. 8: *Performance of subset of 460 SICCAS crystals. The main reasons for failure can be classified into three categories: 1) Light Yield @420nm < 60%, 2) chips, cracks, marks of old labels, 3) Bubbles and other internal defects*

In parallel, we have been characterizing further rectangular crystals from Crytur for optimization of properties like light yield. One avenue is a controlled surface de-polishing. Crytur has experience and good results on perovskites in shape of barrel with this method, but needs to find the right technique for PWO prism and appropriate roughness. In the perovskites case with this technique one can increase the light up to 30% and non-uniformity along the length (for length of 100-150mm) can be below 3%. Initial results for crystals that were mechanically de-polished are promising as illustrated in Fig. 9. Our procurement for 450 crystals in collaboration with the NPS project was delayed as discussed above. We hope to complete a purchase or a large set of crystals over the next year.

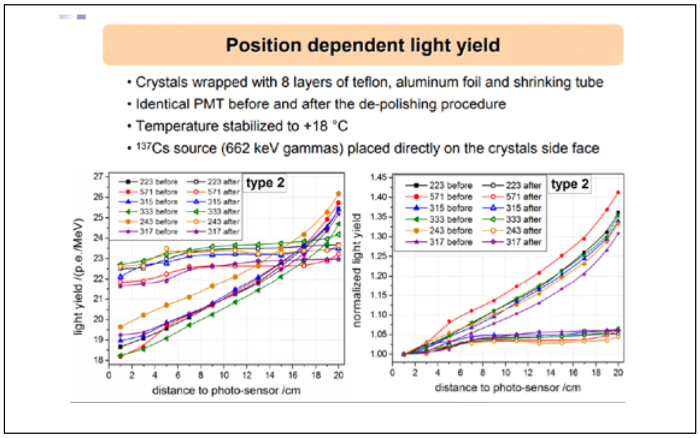


Fig. 9: *Initial light yield results for crystals mechanically de-polished*

Light Collection Non-Uniformities with tapered crystals

The NPS crystals and crystals foreseen for the EIC are of rectangular geometry. A clear advantage of this over a tapered geometry that is necessary for barrel calorimeters is that the measured light yield does not depend on the distance of the location of energy deposition to the photo sensor. This non-uniformity is caused by the interplay of absorption and focusing effects, which influences the amount of scintillation light reaching the readout interface. The non-uniformities can be investigated, e.g. in a first approach through simple optical calculations. However, if the geometry of the detector does not demand a tapered shape, as is the case for NPS and EIC, an increase in light yield for rectangular crystals via other methods, e.g. the de-polishing as described above is preferable.

Sub Project: Scintillating Glass Development for EIC Calorimeter
Project Leader: T. Horn

Abstract

An essential requirement of the Electron-Ion Collider (EIC) calorimeters is to provide adequate energy resolution, which translates into momentum resolution and reconstruction, over a wide kinematic range, as well as particle identification in the forward and backward directions [1-2]. This sets the EIC calorimeters apart from many others. Early R&D for the central/barrel region is essentially complete, and progress is being made to get reliable $PbWO_4$ crystals that would be compatible with EIC requirements at small angles in the forward and backward regions. At larger angles, where resolution requirements are less stringent, glass ceramic scintillators provide an attractive and cost effective option.

Glass ceramic scintillators have been investigated over the last five decades for various applications, e.g., in industry, for medical diagnostics [3] and in oil well logging [4]. However, the requirements for glass in industrial applications differ from the needs of an EIC, in particular in terms of light yield and uniformity for energy resolution, size, timing, and radiation resistance. R&D is ongoing in industry and for scientific instrumentation [5-16]. Some of the most promising materials investigated are cerium doped hafnate glasses and doped and undoped silicate glasses and nanocomposite scintillators. All of these have various shortcomings that include, lack of uniformity and, macro defects, as well as limitations in radiation length, density, radiation resistance, and timing. One of the most recent efforts is DSB:Ce, which is a cerium-doped glass nanocomposite. Small samples of this material have been shown to be in many aspects competitive with $PbWO_4$. However, the issue of macro defects, which can become increasing acute on scale-up, and radiation length remain. A future EIC glass-ceramic-based calorimeter can benefit from many aspects of this very promising R&D, but also presents its own unique set of challenges and priorities that will need to be addressed.

The proposed R&D has two main goals. ***The first is to identify what would need to be done to be able to build a cost effective glass-ceramic calorimeter for the outer endcaps and central regions of the EIC.*** The key question is whether glass ceramics can be produced to provide sufficient resolution, fast response, and radiation hardness. ***The second goal is to investigate the possibility of pushing the performance of glass ceramics towards crystals.*** This would be required if one would extend the outer endcap section towards smaller angles providing considerable cost saving and reducing manufacturing uncertainty. A natural starting point for the proposed work is DSB:Ce since published characterization data indicate that such a material can be competitive with $PbWO_4$. The present work would therefore focus initially on addressing the above noted shortcomings, particularly in uniformity, and demonstration of the ability to scale up to detector elements of the dimensions likely to those required for the EIC. In parallel, formulation modifications will be

investigated with the objective of further optimizing the properties of this family of materials. ***Another aspect of this R&D is to determine the potential for using glass ceramics in a complementary second detector.***

The proposed R&D effort fits naturally into the global EIC calorimeter R&D program, and in particular the ongoing efforts on homogeneous calorimeters. The R&D project presented here will be part of the eRD1 Calorimeter Consortium.

1. Physics Requirements and Calorimetry

1.1 Overview

The physics program of an EIC includes inclusive measurements, which require detection of the scattered lepton and/or hadrons of the scattered hadronic debris for which E-p_z is different from zero; semi-inclusive processes, which require detection in coincidence with the scattered lepton of at least one (current or target region) hadron; and exclusive processes which require detection of all particles in the reaction with high precision [1,2,17-19]. ***For design and placement of calorimetry at an EIC, this means that one has to pay attention to the requirements on particle identification and precision in reconstruction, which is correlated with energy resolution, in different regions of the produced particles' angle and momentum distributions. The available space in each region and material cost are also of considerable importance.***

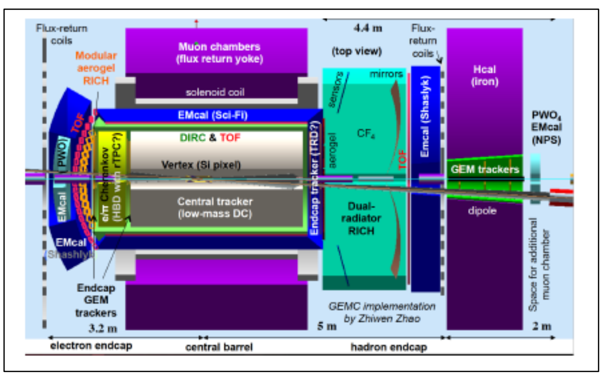


Fig. 1: Example layout of the EIC detector base design

As shown in Fig. 1, the central detector has three regions, backward (electron-going) covering rapidity of $-4.0 < \eta < -1.0$, barrel covering rapidity $\eta = -1.0$ to 1.0, and forward (ion-going) covering rapidity of $1.0 < \eta < 4.0$[2]. In the endcaps, particle identification is important for discriminating single photons from, e.g., Deeply Virtual Compton Scattering (DVCS) and two photons from π^0 decay, and e/p. Electron ID requires electromagnetic calorimetry in the endcap. For DVCS, the photon

[2] Here, the hadron beam goes in the positive z direction (0°) and the electron beam in the negative z direction (180°). Particles with positive p_z have positive values of pseudo-rapidity, $\eta>0$, and particles with $p_z<0$ correspond to $\eta<0$

measurement requires electromagnetic calorimetry as well. Simulations (see Fig. 2) show that a rapidity coverage -4 < η < 1 is required to capture scattered electrons for Q^2>1 GeV^2 and DVCS photons. Resolution is essential for particle reconstruction, which is driven by the need to accurately reconstruct the four-momentum of the scattered electrons at small angles, e.g. η<-3 for DVCS at low *x*. For a critical angle (rapidity), η~-2, the required energy resolution should be (1.0-1.5%)/√E +0.5% (see Fig. 4). At larger angles the requirements of energy resolution may be relaxed to 7%/√E [7]. To distinguish photon from proton and to detect high-*x* Semi-Inclusive DIS (SIDIS) events similar requirements apply in the forward direction. A range of angles -4 < η < 5 covers almost the entire kinematic region in p_T nd z that is important for physics. In the barrel a considerably worse energy resolution, 10-12%/√E is allowable [19]. The regions and functions of the EM calorimeters envisioned for the EIC are:

1. ***Lepton/backward direction:*** detect the scattered lepton with very *high energy resolution*, which translates into high momentum resolution. At rapidity η ~< -2 the energy measurement comes mainly from the calorimeter. The segmentation has to be good enough for particle identification, e.g. to separate proton and photon from DVCS.
2. ***Ion/forward direction:*** detect high-*x* SIDIS particles and the electromagnetic part of high-*x* jets with high resolution
3. ***Barrel/mid rapidity:*** provide particle identification for leptons in a region where the hadron background is large. These include photons from DVCS, vector mesons, π^0 electromagnetic part of jets

1.2 Lepton and Ion Direction ***Inner*** *and* ***Outer*** *Endcap EM Calorimeters*

The choice of calorimetry at backward rapidity -4 < η < -1 is driven by the requirement to detect the scattered lepton with high energy resolution, which for rapidity < -2 is determined by the calorimeter alone. Furthermore, the granularity of the calorimeter has to be good enough for particle identification, e.g. to separate proton and photon from DVCS. Calorimetry at forward rapidity 1 < η < 3.5 is driven by the need to identify hadrons produced in semi-inclusive processes, in particular at large *x*. In both cases, relaxed resolution would be acceptable at larger angles (rapidity).

Fig. 2(left) shows the momentum vs. rapidity distributions in the laboratory frame for photons originating from DVCS for different lepton and proton beam energy combinations. For lower lepton energies, photons are scattered in the forward (ion) direction. With increasing lepton energy, photons increasingly populate the central region of the detector. At the highest lepton beam energies, photons are even produced backward (in the lepton-going direction), very close to the electron cluster. Overall, a rapidity coverage of -4 < η < 1 is needed for DVCS photons and also for the detection of scattered electrons. The general patterns of the kinematic distributions of hadrons produced in semi-inclusive processes are shown in Fig. 2(right). A kinematic coverage of $-4 < \eta < 3.5$ covers the region in p_T and z that is important to achieve the EIC physics goals: TMD, helicity PDF, FFs (with flavour separation), di-hadron correlations, kaon asymmetries, multiplicities, etc.

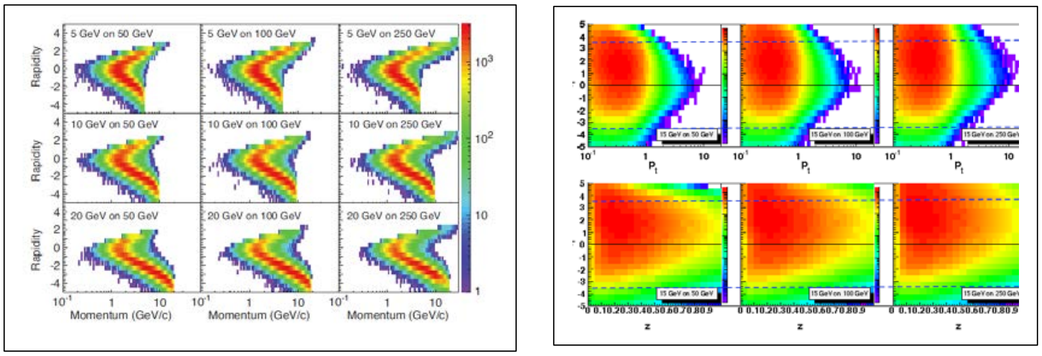


Fig. 2: (left) Energy vs. rapidity for DVCS photons and (right) the SIDIS kinematic coverage for pions with cuts Q^2>1 GeV^2, $0.01 < y < 0.95$ and p> 1 GeV

Fig. 3 shows the combination of high-resolution calorimetry at small angles, where the tracking resolution is poor, and calorimetry with more relaxed requirements at larger angles. The quality of the physics measurement is determined to a large extent by the level of bin-to-bin migration in the 2D (x_{bj}, Q^2) kinematic plane. Past experience, in particular the HERMES Collaboration, indicates that acceptable “bin survival” level[3], which effectively determines the kinematic reach, should be of on the order of at least 0.6-0.7, spanning from the maximum values of y down to the region of $y \sim 0.01$[4].

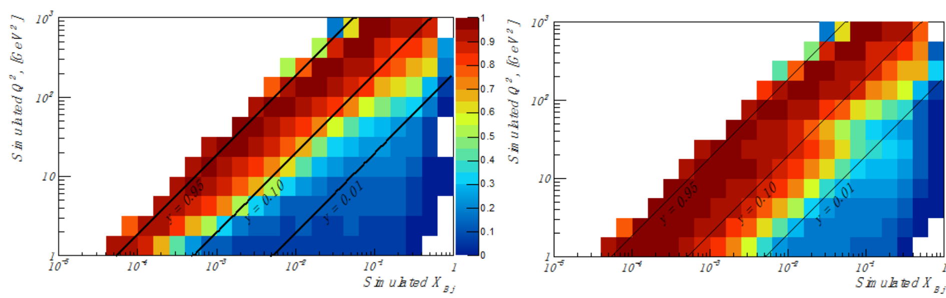


Fig. 3: *Inclusive DIS event parameter migration in the {x_{bj}, Q^2} kinematic plane. Pythia 20x250GeV events, external bremsstrahlung turned off. Only the area with survival probability >0.6-0.7 is suitable for the conclusive analysis. Left panel: only the tracker information is used to calculate scattered electron momentum. Right panel: same events, but a weighted mean of the tracker momentum and the calorimeter energy is used. Calorimeter resolution is taken to be $\sigma_E/E \sim 2.0\%/\sqrt{E}$ for pseudo-rapidity below -2.0 and $\sim 7.0\%/\sqrt{E}$ for the rest of the acceptance.*

A high resolution crystal calorimeter for $\eta < -2$ ($PbWO_4$ crystals) improves the available y range considerably. ***At rapidity $-2 < \eta < 1$ the resolution requirement can be relaxed and could be achieved by a sampling calorimeter with glass-ceramics as a***

[3] Probability to register the event in the same kinematic bin where it occurred originally
[4] where y is the DIS variable, describing a fraction of the beam electron energy carried by the virtual photon

cost effective and easy to manufacture active material. The key questions are if the uniformity of glass ceramics is sufficient to provide the required resolution, if the glass ceramic response time is fast enough, and if the glass ceramics can deal with the expected radiation dose in the endcaps. Results from small samples are encouraging. The glass-ceramics are relatively fast, show good radiation resistance, and excellent temperature stability. The currently limiting factor is light loss, which appears to be related to inhomogeneities arising in the manufacturing process. ***As part of this R&D project our goal is to optimize the glass-ceramic composition, investigate causes of inhomogeneity, and develop an optimized manufacturing process.*** The matching between different materials at small and large angles is an important consideration in the design of the endcap calorimeters. ***As another part of this R&D we will study the optimal configuration for physics output of a high resolution crystal inner calorimeter and a lower resolution glass-ceramic based outer calorimeter using a Monte Carlo simulation.*** Globally, the optimal solution for the endcaps, enabling high-impact DVCS and high-x SIDIS measurements, would be a combination of an inner ($PbWO_4$ crystal) and outer (glass) calorimeter with the following requirements.

The ***inner*** EM endcap calorimeter for rapidity $\eta < -2$ should provide:

1. Good ***resolution in angle*** to at least 1 degree to distinguish between clusters,
2. ***Energy resolution*** < (1.0-1.5 %/√E+0.5%), measurements cluster energy
3. ***Time resolution*** to < 2ns
4. Cluster threshold: 10 MeV
5. Withstand radiation down to at least 1 degree with respect to the beam line.

The ***outer*** EM endcap calorimeter for rapidity $-2 < \eta < 1$ should provide:

1. ***Energy resolution*** to 7%/√E for measurements of the cluster energy
2. ***Compact readout*** without degrading energy resolution
3. ***Readout segmentation*** depending on angle

To make a clear positive impact on the scattered electron kinematics determination, a crystal calorimeter ($PbWO_4$) in the endcap should have a constant term of at most ~0.5%, while a stochastic term on the order of 1.0-1.5% would suffice. This is illustrated in Fig. 4.

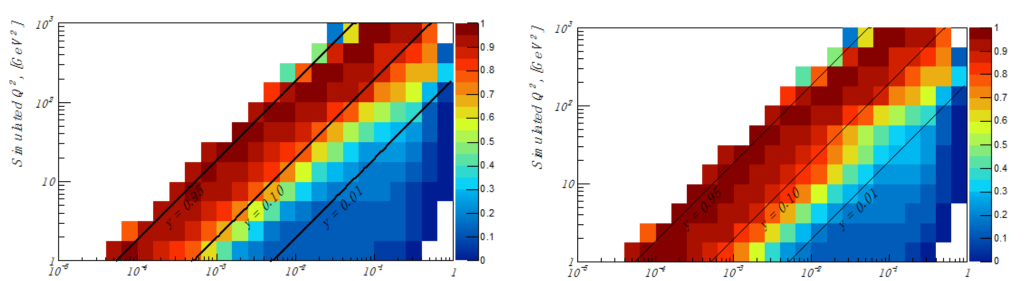


Figure 4. *Same set of events as in Fig.5. Weighted mean of the tracker momentum and the crystal calorimeter energy is used. Left panel: calorimeter resolution is taken to be $\sigma_E/E \sim 1.75\%/\sqrt{E} + 1.15\%$ (PrimEx $PbWO_4$ calorimeter at JLAB [20]) for pseudo-rapidity below -2.0 and $\sim 7.0\%/\sqrt{E}$ for the rest of the acceptance. Right panel: "ideal" calorimeter resolution $\sigma_E/E \sim 1.0\%/\sqrt{E} + 0.5\%$ for $\eta<-2$.*

As discussed in Section 2, the properties of initial glass ceramics samples appear to be competitive with and sometimes even better than $PbWO_4$ crystals regarding optical transmittance and radiation resistance, as well as light yield and temperature stability. The latter is an area where there is a clear gain over $PbWO_4$, whose light yield depends on temperature at 2%/°C and requires continuous monitoring. ***Two key aspects have to be addressed if glass ceramics are to be an alternative to $PbWO_4$. One is homogeneity of the material, which is related to the manufacturing process.*** Samples that have been prepared to date have bubbles and other non-uniformities in the bulk that result in multiple refractions of light and thus impact resolution. A promising avenue that we plan to pursue as part of this R&D is the optimization of the thermal treatment of the glass, which we have shown that, in combination with pre-treatment of the dopants, can significantly improve uniformity. Another aspect is containment of the longitudinal shower, which is related to radiation length. To detect photons in the GeV range as required by EIC, a detector size of ~20cm would be desirable[5]. As part of this R&D, we plan to explore glass compositions and processing conditions that are optimized to yield reduced radiation length. Other optimizations of the glass production process that we plan to pursue include the introduction of activator ions and balancing them with heavy ions in both glass and crystalline regions. With a final high performance glass, a larger area towards smaller angles could be covered in the endcaps that may yield considerable cost savings [6] and greater manufacturing certainty compared to $PbWO_4$ crystals[7]. An important benefit of glass as a base material for scintillators is that the manufacturing process is considerably faster, and therefore cheaper, than that for, e.g., crystals.

1.2 Barrel EM Calorimeters

The choice at central rapidity is driven by the need to provide particle identification in a region where hadron background is large. Measuring the ratio of the energy and momentum of the scattered lepton typically gives a reduction factor of ~100 for hadrons. In this region the energy measurement can be supplemented by tracking detectors, and noticeably worse energy resolution of the calorimeter suffices.

Fig. 5 shows the momentum distribution for the scattered lepton for different rapidity bins and three different lepton-proton beam energy combinations. The $Q^2 < 10$ GeV^2 events typically correspond to negative rapidity ($\eta < -3$) and $Q^2 > 10$ GeV^2 correspond to rapidity $\eta > -2$ for 5 GeV x 50 GeV and $\eta > -2$ for 30 GeV x 50 GeV. Depending on the center-of-mass energy the rapidity distributions for hadrons (both charged and neutral) and the scattered lepton overlap and need to be disentangled.

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[5] Current glass radiation lengths range from 2-4 cm, which would require modules of length 60-70cm to minimize light loss, and thus to retain high resolution

[6] The cost of glass is estimated to be <\$1/cm^3, while that of $PbWO_4$ currently ranges from \$15-25/cm^3

[7] As discussed by the crystal eRD1 project, there is large pricing and manufacturing uncertainty as there are only two vendors, one in China with considerable quality control uncertainty, and one in the Czech Republic that remains to demonstrate capability and quality control for mass production

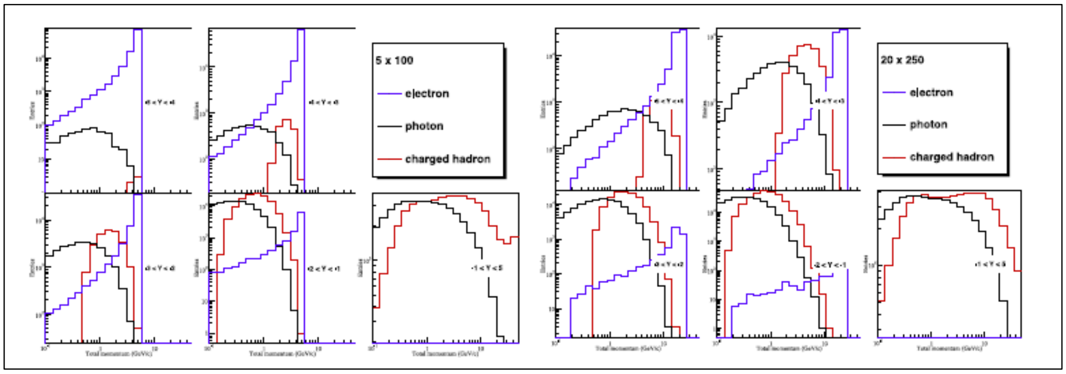

Fig. 5: Distribution of the total momentum for electrons, photons and hadrons.

For example, for the higher center-of-mass energy, electron rates are a factor of 10-100 smaller than photon and charged hadron rates, and comparable again at a 10 GeV/c total momentum (See Fig. 7.18 in the EIC White Paper [9]). This adds another requirement to the detector: good electron identification. To satisfy the PID[8] requirements in the barrel, EM calorimetry should provide [19]:

1. ***Compact design*** as space is limited
2. ***Energy resolution*** < (10-12%/√E) for leptons where hadron background is large

In the central region, a segmented calorimeter with glass as an active material could be a cost effective option. The key question here is integration of glass with other materials and detectors.

2. Proposed R&D

In this work, we propose, in collaboration with universities and small businesses, to investigate scintillating glasses and/or ceramics as an active calorimeter material for the outer endcap and central region EIC calorimeters. These materials are more cost effective and easier to manufacture than, *e.g.*, crystals. Initial samples show very promising and competitive properties, but further R&D is needed to develop them with sufficiently high density and to consistently meet the EIC requirements on uniformity, timing, and radiation resistance. The concept of a glass-ceramic-based calorimeter is independent of EIC implementation and would work at either eRHIC or JLEIC.

2.1 Development of a Cost Effective Glass Scintillator

2.1.1 Production of Glass Scintillators at CUA

At CUA, we have produced initial samples of glass ($BaO*2SiO_2$) and glass ceramics (DSB:Ce)[9]. The transparent glass ceramics contain nano-size particles of $BaSi_2O_5$, which improve scintillation properties of the material. The Ba-Si system allows to incorporate trivalent ions such as Lu, Dy, Gd, Tb, Yb, Ce, which, in the

[8] Particle IDentification
[9] Glass ceramic is a glass that contains microcrystallites produced through thermal treatment

appropriate concentrations, favorably impact light output, timing, and radiation resistance. The technology used is glass production combined with successive thermal annealing. The nano-crystallites are produced during the latter. The process is very sensitive to temperature and annealing time. The annealing time must be optimized for a given glass composition to nucleate and grow nano-crystalites, but to prevent their dimensions from increasing beyond nanometer scale, which negatively impacts the material transparency.

Neutron sensitive scintillation detectors including glass with nano-crystallites have been produced previously for the oil well logging industry. There, the emphasis is on transparency and scintillation light output per unit of absorbed energy of thermal neutrons (0.025 eV). To this end, the glass matrix typically contains a relatively high concentration of ^{6}Li or ^{10}B. While conversion efficiency is important in this application, and at some level uniformity, the requirements are much relaxed compared to those of the EIC. This includes rates and therefore timing. Radiation resistance focuses on hadrons, while EIC radiation also has a dominant electromagnetic components.

Glass-based scintillators have also been explored for future calorimeters at the LHC. The approaches include heavy metal fluoride glasses, which when doped with cerium, have been shown to reach radiation lengths of 1.6 cm, decay constants of 25 ns, small temperature dependence of the light yield (0.4%/C), and have been shown to be radiation hard up to 6 kGy. Other materials investigated are doped and un-doped phosphate and silicate glass-based nanocomposite scintillators. All of these share similar shortcomings, which include at least one of the following: macro defects, unfavorable radiation length compared to crystals, timing, transparency, and inhomogeneity. These shortcomings have thus far not allowed for producing glass ceramic scintillators suitable for Nuclear Physics or High Energy Physics Experiments. One of the most recent promising materials, DSB:Ce, still shows macro defects and inhomogeneity, as well as unfavorable radiation length.

Addressing these issues requires a detailed understanding and optimization of the manufacturing process, which is one of the goals of the present R&D. The experience from the previous DSB R&D efforts for potential LHC applications will provide a beneficial starting point for the present work. However, as is the case for industry application, LHC requirements are different from those of the EIC, for example focusing on stoichiometry optimization to make the material resistant to hadron radiation. Similarly, glass-ceramic-based scintillator materials for potential EIC applications will have to be developed and optimized for EIC specifications and tested under appropriate conditions.

In the present work, we plan to produce glass and glass ceramics with properties optimized to meet EIC requirements. Initially, small samples will be produced allowing for quick evaluation and benchmarking. The properties will be tuned through a combination of composition variations and the heat treatment protocols that are employed to induce nanocrystallization. Based on these results, we will investigate the production of larger samples and identify and address scale-up issues in order to define a practical production process for detector elements of the dimensions required for the EIC. The larger glass samples could be used in prototype tests (section 2.1.3) to establish the limiting energy and position resolution.

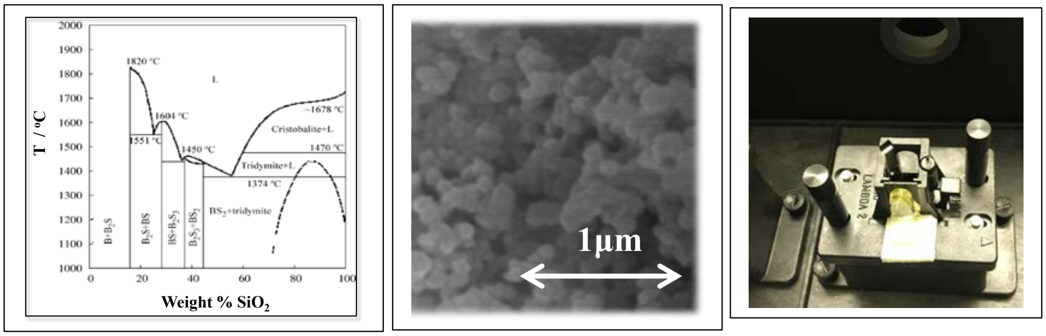

Fig 6: *(left) Phase diagram of the $BaO*SiO_2$ system, (middle) SEM image of recrystallized $BaO*2SiO_2$ at 950°C, (right) small sample in transmittance measurement setup*

Material/ Parameter	Density (g/cm^3)	Melt. Point (°C)	Rad. Length (cm)	Moliere Radius (cm)	Interact Length (cm)	Refr. Index	Emission peak	Decay time (ns)	Light Yield (γ/MeV)	Rad. Hard. (krad)	Radiation type	Z_{Eff}
(PWO)$PbWO_4$	8.30	1123	0.89 0.92	2.00	20.7 18.0	2.20	560 420	50 10	40 240	>1000	.90 scint. .10 Č	75.6
TF-1 Lead Glass	3.85	1100 1200	2.6 2.7	3.3 3.7	21.8	1.65	300 350	<40	1-2	10	Pure Č	44.9
F-101 Lead Glass	3.86	1200	2.78	3.28	~22	1.65	450 500	40 50	1-2	50	Pure Č	44.3
(BaO*2SiO2):Ce glass	3.7		3.6	2-3	~20		440, 460	22 72 450	>100	10 *(no tests >10krad yet)*	Scint.	51
($BaO*2SiO_2$):Ce glass loaded with Gd	4.7-5.4		2.2		~20		440, 460	50 86-120 330-400	>100	10 *(no tests >10krad yet)*	Scint.	58

Table 1: *Properties of initial glass ceramic samples in comparison to $PbWO_4$ crystals and two commonly used types of lead glass. $PbWO_4$ is the material of choice for the EIC small angle endcap calorimeters. The small glass ceramic samples outperform lead glass and are competitive with $PbWO_4$. Key questions for glass-ceramics for use in EIC calorimetry are homogeneity and radiation length, which are related to composition optimization and manufacturing process.*

2.1.2 Evaluation of Glass Quality

We will test the performance of glass, and in particular, measure light yield, optical transmission, uniformity and radiation hardness in context of EIC requirements. The spectroscopic and scintillation properties will be measured using PerkinElmer Lambda UV/Vis spectrophotometers with double beam, double monochromator, and a large sample compartment. The spectrometers allow for measurements of the transmittance and absorption between wavelengths of 250 to 2500 nm with 1 nm resolution. The systematic uncertainty in reproducibility of the transmittance measurements is on the order of 0.2%. The light output will be measured with a Photonis XP2262 PMT with a bi-alkali lime glass window. For the light yield measurements, a collimated Na-22 source will be used to excite the samples. Radiation resistance measurements will be carried out in collaboration with the Vitreous State Laboratory (VSL). These include radioactive sources and an X-ray irradiation system. Material characterization including determination of trace element impurities, defects, oxygen vacancies and structural analysis is also carried out in collaboration with the VSL. These studies use a combination of different instruments owned by the VSL, e.g., XRF, TEM and SEM, as well as Raman spectroscopy and Raman/AFM microscopy. VSL also brings extensive glass formulation, melting, heat treatment, and cutting and polishing facilities and experience.

Through collaboration with the Laboratoire de Chimie Physique at Orsay the group has access to a panoramic irradiation facility based on 3000 Cu Co-60 sources. This facility can provide dose rates ranging from 6 to 5000 Gy/h. Thus, high total doses can be accumulated in a short period of time and the effect of different photon irradiation rates can also be studied. In addition, IPN-Orsay houses several beam facilities that can be used to further study the effects of radiation on $PbWO_4$ blocks. Firstly, a 50 MeV electron facility (ALTO) can provide up to 1 microA of electrons that can complement the irradiation tests made with photon sources. Secondly, a proton (and several ions) accelerator of the "Van de Graaf" type (Tandem) can provide proton energies in the range of tenths of MeV. This facility is also readily available and will provide information on the crystal damage induced by hadrons, important for the future EIC.

The INFN group has access to instrumentation and equipment required for readout tests of the glass ceramics (adaptable crystals array, VME-VXS crate, HV power supply, ...) and is planning to provide other light readout sensors useful to characterize glass samples (PMTs) and test alternative options (APDs, SIPMs) with a full optimized data acquisition chain (analogic pre-amplification and digitization). With these, the group has all the capabilities to evaluate the optimal readout for glass ceramics finding the best match between light emission spectra and photo-sensor sensitivity. The test setup will be calibrated with an array of $PbWO_4$ crystals whose performance is known and compared side-by-side with the proposed technology.

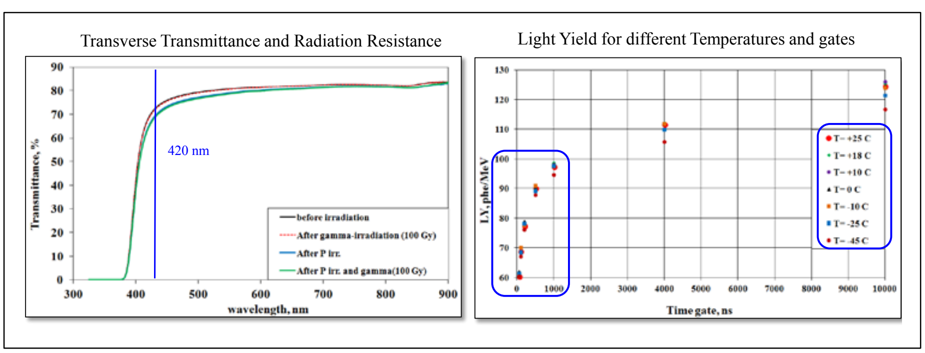

Fig 7: *(left) Transverse transmittance before and after irradiation with electromagnetic and hadron radiation with integrated dose of 100 Gy, (right) light yield as a function of integrating gate for temperatures between -45 and 25 °C. While these properties seem competitive with crystals, uniformity remains a concern suggesting that the manufacturing process needs optimization.*

The properties of initial glass samples are shown in Table 1 and Fig. 7[10]. Optical properties, radiation resistance, light yield and temperature stability seem competitive with crystals. In particular, the insensitivity to temperature is an advantage over $PbWO_4$, which has a dependence of about 2%/°C, which has to be continuously monitored. The glass ceramics are relatively fast and show good radiation resistance, both properties that make them, along with light yield, more competitive than lead glass. A key aspect for glass-ceramics in EIC detectors is homogeneity of the material, which is correlated with calorimeter resolution. Current samples have non-uniformities whose origin can be traced to details of the manufacturing process. The current Moliere radius of the glass samples, important for transverse shower containment, is comparable to lead glass and 2-3 cm (2cm for $PbWO_4$). For distinction of two photons from π^0 decay in the endcaps, a granularity of at least 35x35mm^2 is needed. The initial glass samples are within the limits of this requirement. However, further optimization is needed to meet requirements for all configurations and EIC kinematics. The current radiation length of the glass samples, important for longitudinal shower containment, is 2-4cm (1cm for $PbWO_4$). This impacts the compactness of the detector as detection of photons of a few GeV would require modules of length 60-70cm (20cm for $PbWO_4$). This could be sufficient in a sampling calorimeter assembly (outer endcaps and central region), but the resulting resolution, in particular at lower energies, would not be competitive with a homogeneous $PbWO_4$-based configuration (endcaps at smaller angles). As part of this R&D we plan to optimize the glass composition for higher density and thus lower radiation length, as well as to explore whether a sampling configuration with glass as active material may be sufficient for outer endcap and central regions.

2.1.3 Construction and testing of a prototype detector

A measurement with a prototype will allow us to establish the limiting energy and position resolution of the material – by comparing measured to expected light output. We plan to use the prototype together with simulations to evaluate contributions to the overall resolution including uniformity of glass response and statistical fluctuations of containment losses. These studies will naturally include calibration of the precision among glass stacks, dependence on incidence angle and spacing between the glass blocks.

Energy and position resolution can be established in a test beam. The prototype could be calibrated with the tagged photon beam at Jefferson Lab. The basic principle of this test program is as follows. One tags the bremsstrahlung produced by a monoenergetic electron beam up to 11 GeV. After bremsstrahlung emission, the electrons are analyzed by the magnetic spectrometer of the tagger requiring a coincidence of the bremsstrahlung photon with the corresponding electron in the focal plane.

[10] These tests were carried out at Giessen U. by R. Novotny and V. Dormenev [9], our collaborators on the JLab NPS project

 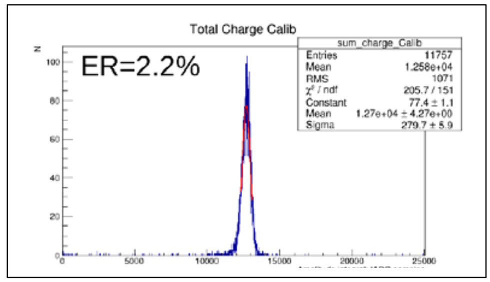

Fig 8: *(left) NPS 3x3 $PbWO_4$ prototype installed in Hall D at Jefferson Lab in 2018, (right) result for 4.69 GeV electrons from the initial energy calibration in April 2018 before optimization.*

The NPS 3x3 $PbWO_4$ shown in Fig. 8 (NPS 10x10 $PbWO_4$ or the envisioned EIC 5x5 prototype) array is composed of 9 rectangular blocks (100 or 25 blocks, respectively), 200mm long and of 20x20 mm^2 cross section. The 3x3 prototype could be easily adapted for prototype studies with glass. The prototype includes a temperature monitoring system and could also be used to investigate temperature sensitivity of the glass. The glass prototype would be located at a position downstream of the radiator. A set of collimators can be used to control the beam spot on the front face of the glass blocks. The glass matrix could be moved via remote control in two dimensions perpendicular to the axis of the collimated photon beam by stepping motors to perform a relative calibration of each detector element. This technique has previously been used successfully for the Primex HyCal and at MAMI for tests of PANDA ECAL prototypes, and recently in March-May 2018 for NPS $PbWO_4$ prototype tests[11].

2.2 Initial Development of a High-Performance Glass Scintillator

Globally, efforts on ceramic scintillators and scintillating glasses can be traced back more than three decades. Many of these efforts were focused on ceramic materials for PET, since the size of the crystals for PET is much smaller and easier to achieve better quality than for Nuclear Physics or High Energy Physics applications. The general aspects of material and manufacturing are, however, similar. The common shortcoming of the materials and production process for these materials has been inhomogeneity and macro defects, and unfavorable radiation length. Others include timing, radiation hardness, and transparency. With the recent production of DSB:Ce it has been demonstrated that small samples can be produced that are competitive with $PbWO_4$ crystals. The critical aspects to address are to determine the origin of inhomogeneities and macro defects in the production of large samples and to develop a process to eliminate them. Another aspect is to optimize the glass

[11] The authors from CUA, IPNO and Yerevan have carried out these prototype tests and are part of the NPS collaboration

composition to meet EIC specifications, e.g., Ce/Gd ratio to increase sensitivity to EM probes. For glass ceramic scintillators to be suitable for a high-resolution homogeneous EIC calorimeter, e.g. as alternative to $PbWO_4$ crystals, the understanding of the optimization of composition, e.g. Ce/Gd concentrations, and origin of inhomogeneities in the manufacturing process and its optimization are mandatory. Optimization of the radiation length of the material could also be beneficial. Both of these are related to resolution. As an example, it would be desirable to establish better timing resolution of the material and to further increase its radiation hardness.

2.2.1 Increasing the resolution

The dominant factor for high resolution at small angles in the endcap calorimeters is sufficient light yield and uniformity (for 1-1.5%/$\sqrt{E}$) and keeping the constant term small (~0.5%). The most straightforward way to increase the light yield is through optimizing the balance between absorber and activator ions in the glass. Uniformity of the composition is also of considerable importance [11]. We will investigate possibilities to optimize the manufacturing process, e.g. concentrations, annealing temperatures and times for this and the feasibility of scale up for mass production. The key measurements to characterize the individual properties of glass samples include light yield as function of integration gate and temperature, longitudinal and transverse transmittance, and radiation resistance for an integral dose of 100 Gy. These test basic luminescence/scintillation properties in relation to Ce/Gd concentration. To determine the energy response and resolution of the material for GeV photons as anticipated for EIC, a glass matrix (prototype) of large blocks needs to be constructed. The response function can be measured with energy-marked photons at Jefferson Lab. The readout is an important consideration. Our studies with $PbWO_4$ will be an important benchmark. The current result for DSB:Ce for 90 MeV photons measured at MAMI is 30% (~3%/1GeV assuming linear). The simulations we developed for $PbWO_4$ resolution studies, e.g., the impact of dead zones and miscalibration on energy resolution, and in particular the constant term, could be adapted to address the impact of these on the glass matrix.

2.2.2 Precision Timing

The decay kinetics of glass scintillator depends on the doping concentration, e.g. with Gd. Studies have shown that smaller Gd content will have slower kinetics and increase with increased concentration. However, there is a saturating content that will actually lead to shortening of the scintillation kinetics. We will explore doping with Gd and other efficient transporters of excitations. Key measurements to establish precision timing are light yield as function of integration time and concentration of Ce/Gd.

2.2.3 Simulation Studies

An important consideration for feasibility of covering a larger area towards smaller angles in the endcap, is whether glass will be sufficiently radiation hard for dealing with the expected radiation dose. At present, there is no detailed or accurate estimate of the dose for the endcap calorimeter at EIC. There are estimates of particle production over a wide range of rapidity, which can be found on the EIC Wiki page and these rates can be used to estimate the energy deposit (and hence the dose) from charged and neutral particles (photons, neutrons and K^0_L's) produced by beam interactions. We plan to model this to some level and make preliminary estimates of the dose, but we expect that this will be an ongoing effort to continuously refine these estimates as the model of the detector and IR evolves.

2.4 Synergies with Ongoing Crystal R&D

The hardware and glass production R&D makes substantial us of synergies with crystal calorimeter development for the Neutral Particle Spectrometer (NPS) at Jefferson Lab and ongoing research at the VSL. An example is the testing of glass and crystals. The CUA NP group and the VSL own a $60K spectrophotometer and a $100K light yield testing setup with sources and DAQ. In addition, a multi-million dollar state-of-the-art glass production, characterization, and chemical analysis facility is available for this R&D.

3. R&D Timeline and Deliverables

Table 2 R&D Timeline and Deliverables

	FY19 by Quarters				FY20 by Quarters			
Deliverable	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
Produce small glass samples	X							
Glass quality tests		X	X	X			X	X
Radiation Damage studies		X	X	X			X	X
Produce larger glass samples			X	X	X			
Construct prototype and tests				X	X	X		X
High performance glass studies						X	X	X
Simulation Studies			X	X			X	X
Investigation of glass in PID								X

4. Responsibilities

- CUA/VSL - Lead Institution. Coordination of R&D program, glass samples and initial testing
- IPN Orsay – Simulation studies, prototype construction and testing
- INFN – material characterization and readout
- JLAB – provides facilities for radiation studies, prototype and quality measurements as needed
- BNL – provide expertise and facilities for simulation studies and radiation damage measurements (hadron).

- Yerevan Physics Institute – provides expertise for simulation studies

5. Funding Request and Budget

Table 3. Funding by task

Item	**FY19 ($K)**	**FY20 ($)**
Materials for glass production	5	5
Technical Support	15	20
Parts for prototype and construction		10
Travel	10	15
Total	**30**	**50**

Table 4. Funding by Institution

Institution	**FY19 ($K)**	**F20 ($k)**
CUA	15	20
IPN Orsay	10	15
INFN Genova	5	15
JLAB		
BNL		
Total	**30**	**50**

Budget scenarios and impact statement: Our main goal over the next year is to produce glass-ceramic samples and to investigate if glass-ceramics can be made providing sufficient resolution, fast response, and radiation hardness for application in EIC calorimeters in the endcaps and central region. This requires detailed studies and optimization of the manufacturing process. The limiting performance of glass-ceramics can be determined with a prototype, which we plan to construct and use for measurements at JLab. Initial studies of readout optimization are planned as well. The individual steps are listed in Table 2.

In the case of a 20% cut, we would be able to produce and test small glass-ceramic samples and perform investigation and optimization of the manufacturing process. However, we would have to delay the construction and testing with a prototype, which would impact our ability to determine the real limits of position and energy resolution of the glass-ceramic material for application in EIC calorimeters.

In the case of a 40% cut, we would not be able to construct and test a prototype to determine the real limits of resolution of the glass-ceramic material for EIC. Our focus would mainly shift towards the NPS project, which would be the funding source for our activities, and we may only provide information relevant specifically for EIC, as possible.

Manpower:
A list of existing manpower is shown below. These participants are supported by external funds and *not* through the EIC R&D program.

IPN-Orsay
M. Josselin, H. San (graduate student), R. Wang (postdoc), G. Hull, C. Munoz-Camacho

INFN-Genova
M. Battaglieri, A. Celentano, R. De Vita

CUA
S. Ali (graduate student), R. Trotta (graduate student), V. Berdnikov (postdoc), T. Horn, I. Pegg, Vitreous State Laboratory

Yerevan
H. Mkrtchyan, V. Tadevosyan

BNL
C. Woody, S. Stoll

External Funding

- All FTEs required for working towards producing glass samples and major part of glass characterization are provided by CUA/VSL/IPN-Orsay/INFN or external grants. The absence of any labor costs makes this proposed R&D effort extremely cost effective.
- The expertise and use of specialized instruments required for glass characterization and chemical analysis, as well as additional glass samples are provided through the VSL. The VSL has trained and experienced staff and procedures already in place requiring no additional setup overhead.

Salaries and wages are provided by private external grants from the individual principal investigators, e.g., IPN-Orsay, Yerevan, and the National Science Foundation.

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Appendix – Complementary Second Detectors

At the EIC, due to its envisioned high luminosity, systematic uncertainties will be the main limiting factor in extracting the underlying physics. Experience at LEP and HERA has shown that one of the most effective ways to reduce the systematics is to combine data from multiple *complementary* detectors, with critical components exhibiting different behavior in terms of ageing, resolutions, operation in high background conditions, etc. Therefore, as it was suggested several times in the past and confirmed during the recent EIC User Group Detector Discussion Meeting at Temple University, the EIC community supports the idea of having at least two complementary general-purpose detectors *utilizing different detector technologies.*

Glass could be a cost effective option for such a complementary detector. The key questions here are whether glass ceramics would be sufficiently dense and fast. We plan to investigate the potential of glass-ceramics for these detectors. As an example, the requirements of the TOPSiDE electromagnetic calorimeter [21] include:

1) modules have to operational in magnetic fields, 2) Smallest possible Moliere radius to separate photons from energy deposited by charged particles and neutrons, 3) very fine granularity to identify energy deposits from each particle separately, 4) 10ps timing resolution. Glass could possibly satisfy several of these requirements, but large area photodetector operation in magnetic fields, Moliere Radius, granularity, and timing in the 10 ps range have to be investigated in detail.

Sub Project: Development of a High Density, Fully Projective Shashlik Electromagnetic Calorimeter with Improved Energy, Position and Timing Resolution for EIC
Project Leaders: S. Kuleshov, E. Kistenev and C.Woody

Past

What was planned for this period?

UTFSM planned to produce one 40 X0 and one 20 X0 high density shashlik module and test both of them during the last six month period. We planned to test the 40 X0 module in the test beam at CERN in the spring of 2018 and to test the 20 X0 module at the Detector Laboratory at UTFSM. The modules are comprised of 38 x 38 x 1.5 mm W80Cu20 plates from UTFSM and the same size scintillator tiles provided by IHEP. Each module consists of a 2x2 array of 19 x 19 mm towers that are each penetrated by 4 WLS fibers. Each fiber is read out individually with its own SiPM, which allows a measurement of the shower position within the tower. While the light collection uniformity of this compact tower is expected to be quite good due to the short propagation distance of light from any point in the scintillator to one of the WLS fibers, measuring the position of the shower within the tower enables a position-dependent correction to be performed that can be used to correct for any residual non-uniformity. As a result, we expect the uniformity of the energy response of a compact shashlik calorimeter to be superior to the response of a comparably compact W/SciFi calorimeter. However, this conjecture needs to be verified, both by simulation and by measurements, which is the goal of this R&D effort.

What was achieved?

The design of the high density shashlik modules was completed and most of the materials for constructing the modules were obtained. Figure 1 shows the overall design of the module.

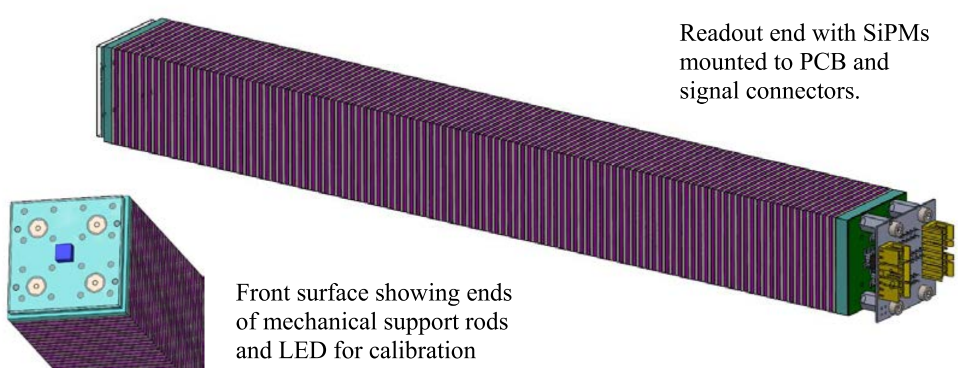

Fig. 1. High density shashlik module consisting of 38 x 38 x 1.5 mm W80Cu20 absorber plates corresponding scintillator tiles read out with WLS fibers and SiPMs.

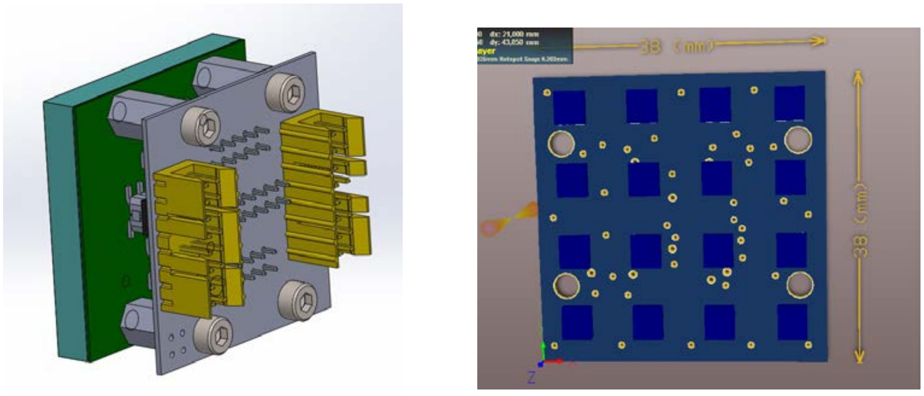

Fig. 2. SiPM readout board and signal connectors. Photo on the right shows the actual PCB with 16 locations for the SiPMs (4 per tower).

Work also continued on the design of the SiPM readout. Figure 2 shows the design of the SiPM readout board and signal connectors. The photo on the right shows the actual PCB for the SiPMs. There will be 16 SiPMs per board corresponding to a 2x2 array of SiPMs for each of the 2x2 towers. Each 3x3 mm2 SiPM will read out one individual WLS fiber for each tower.

Figure 3 shows one of the modules being assembled. The plates are stacked in a fixture alternating with the scintillating tiles. The tiles are coated with a diffusing reflector (70 micron thick white vinyl film) to improve their light collection efficiency and uniformity. Support rods are passed through the stack and secured at both ends and the wavelength shifting fibers are inserted into the holes. The assembly of the modules is continuing and is expected to be completed during the period of this proposal.

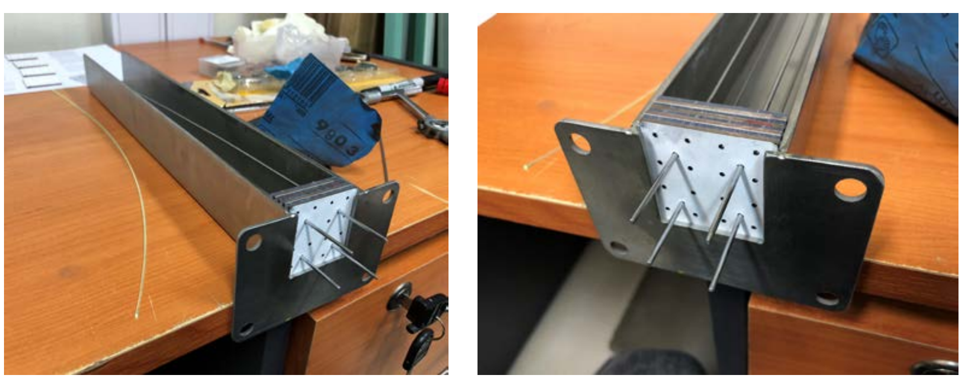

Fig. 3. Assembly of the stack of absorber plates and scintillating tiles. The support rods and WLS fibers are inserted longitudinally along the stack.

What was not achieved, why not, and what will be done to correct?

The construction of the two modules was not completed during the last period but work on them is continuing at UTSFM, albeit at a slow pace. This work is being performed at a very low priority due to lack of funding and support since it is being paid for solely from internal funds at UTSFM. We nevertheless hope to be able to continue this work and complete both of these modules during the next period and also test them if additional funding becomes available.

Future

What is planned for the next funding cycle and beyond? How, if at all, is this planning different from the original plan?

If funding is available, work will continue to complete the two high density shashlik modules and test them during the next period. There should be sufficient funds at UTSFM to complete the mechanical work, but no funding exists to equip the detectors with SiPMs and to test them in the beam. For the 20 X0 module of interest to EIC, these funds would have to be provided through EIC R&D.

If supported, the current EIC R&D plan would be as follows:

- Complete the mechanical construction of the 20 X0 shashlik module at UTSFM.
- Equip the 20 X0 module with SiPMs provided by EIC R&D funding. These would be new, second generation SiPMs with lower noise, less cross talk and reduced after pulsing now currently available in small pixel sizes (10-15 μm) from several manufacturers (e.g., Hamamatsu and KETEK).
- Test the module at UTSFM with cosmic rays using available readout electronics.
- Send the module to BNL for testing with sPHENIX calorimeter readout electronics.
- Use an optical ray tracing program at BNL to study and optimize the light collection efficiency and uniformity of response of the various components of the shashlik readout (scintillating tiles, WLS fibers and SiPMs).
- Study optical readout components (scintillating tiles, WLS fibers, SiPMs and their configuration) in laboratory tests at BNL.
- Study radiation damage of new SiPMs with neutrons and gammas at BNL.
- Refurbish several PHENIX Pb/Sc shashlik EM calorimeter modules at BNL with individual SiPM readout of every fiber and measure light collection efficiency and uniformity. This would give a direct

comparison between very compact high density W/Cu/Sci shashlik modules and larger, lower density Pb/Sci shashlik modules.
- If funding permits, build 5 or more additional W/Cu/Sci modules and equip them with SiPMs. This would allow constructing at least a 2x3 array of blocks (4x6 = 24 towers) that could be tested in the test beam at Fermilab. Additional PHENIX Pb/Sci modules could also be tested in the test beam at the same time for comparison.

What are critical issues?

The most critical issue for the continuation of this R&D is to acquire additional funding from EIC Detector R&D to support this effort. We believe that a significant amount of funding and manpower has already been put into the project using internal funds at UTSFM to develop the overall design and constructed the basic hardware. However, additional support is needed to complete the construction of the first set of modules, test them, and understand their performance. We believe this can be done with a fairly modest level of support, but this will not be completed without additional funding from EIC. We also feel that a significant and important potential benefit has been identified with this technology that could lead to substantial improvements in the light collection uniformity, and hence the energy resolution, for an EIC calorimeter based on this design, which we hope to be able to demonstrate as a result of this R&D.

Additional information:

Manpower

Include a list of the existing manpower and what approximate fraction each has spent on the project. If students and/or postdocs were funded through the R&D, please state where they were located, what fraction of their time they spend on EIC R&D, and who supervised their work.

- Technical work at UTSFM is currently being carried out with approximately 10% of an FTE. This effort is currently limited by internal funding at UTSFM.
- There is currently no technical effort on this project at BNL other than discussions among scientists.

External Funding

Describe what external funding was obtained, if any. The report must clarify what has been accomplished with the EIC R&D funds and what came as a contribution from potential collaborators.

- All manpower at UTSFM is being provided by internal funding.

- Support for a UTSFM engineer to visit BNL for one month would have to be provided though EIC R&D funds.
- All scientific manpower at BNL would be provided by internal funding. However, technician and designer labor would need to be supported through EIC R&D funds.

Publications

Please provide a list of publications coming out of the R&D effort.

None

Budget

Funds are requested from EIC E&D to support the completion of the 20 X0 module and to test it in the lab and in the test beam at Fermilab. If possible, the beam test would be carried out in conjunction with a test of the sPHENIX calorimeters or other EIC calorimeter test at Fermilab in 2019, which would help to greatly reduce the overall cost. Funds are requested for an engineer from UTSFM to visit BNL for one month to help test the module and prepare it for the beam test. Travel finds are also requested for scientists from BNL to visit UTSFM. Technician and designer support at BNL would need to be paid for with EIC R&D funds. The SiPMs for equipping the module and for radiation damage studies would also have to be paid for with EIC R&D funds.

The tables below give the funding requests for the shashlik project for the three funding scenarios of the baseline budget, 20% reduction and 40% reduction.

Baseline Budget

Amount ($K)	Activity
5	SiPMs
5	Misc electronic components (cables, adapter boards, etc)
15	Technical support at BNL (technician, designer)
5	Support for UTFSM at BNL for 1 month
10	Travel (includes support for UTFSM and BNL)
10	Test beam (in collaboration with sPHENIX or other EIC calorimeter test)
50	Total w/o overhead
25	Overhead
75	Total with overhead

Baseline Budget with 20% Reduction

Amount ($K)	Activity
5	SiPMs
5	Misc electronic components (cables, adapter boards, etc)
15	Technical support at BNL (technician, designer)
5	Support for UTFSM at BNL for 1 month
10	Travel (includes support for UTFSM and BNL)
	Test beam (in collaboration with sPHENIX or other EIC calorimeter test)
40	Total w/o overhead
20	Overhead
60	Total with overhead

Baseline Budget with 40% Reduction

Amount ($K)	Activity
5	SiPMs
5	Misc electronic components (cables, adapter boards, etc)
10	Technical support at BNL (technician, designer)
5	Support for UTFSM at BNL for 1 month
5	Travel (includes support for UTFSM and BNL)
	Test beam (in collaboration with sPHENIX or other EIC calorimeter test)
30	Total w/o overhead
15	Overhead
45	Total with overhead